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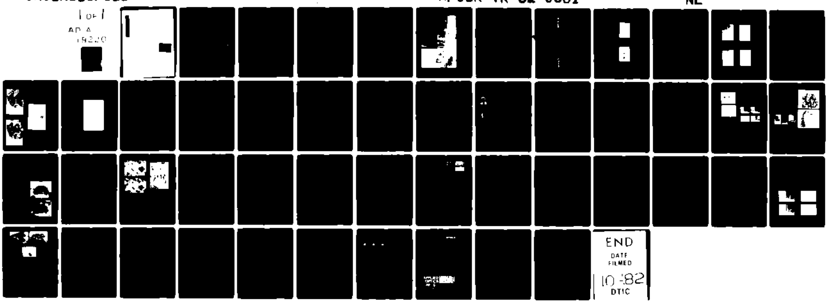

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The first phase of our research program on white-light optical information processing and holography has been completed. In this period, we have synthesized an optical information processing system, which permits complex spatial filtering with a broad band light source. The application of this technique of optical processing with incoherent source to smeared image deblurring was carried out. Since the use of white-light source, we have extended to color image deblurring. We have also

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20. ABSTRACT (Continued)

developed a new technique for image subtraction with encoded extended incoherent source. Color image subtraction with the source encoding of two narrow spectral incoherent sources has also been demonstrated. As compared with the coherent optical processing technique, we had shown that the incoherent source techniques provides better image quality, and very low coherent artifact noise. We have also shown that the incoherent optical processing system is generally economical, versatile, and easier to maintain. We have also in this period investigated the spatial and temporal coherence requirements for the partially coherent processing technique. Several significant results for image deblurring and image subtraction were obtained. For more efficient utilization of an extended incoherent source, a source encoding technique was developed. We have shown that, since the spatial coherence requirement is dependent upon the processing operation, a strict coherence requirement may not be needed for some optical processing operations. Thus, a reduce coherence requirement may be used for a specific processing operation.

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I. Introduction

During the past year, our research in "white-light otpical information processing and holography" has demonstrated several significant results that several of optical information operations can be carried out with non-coherent source. As in the past year, we have been quite consistent in reporting our AFOSR sponsored research in various journals and conference publications. Sample copies of these papers are included in this report as in the following chapters to provide concise documentation of our work. In the following sectins, we will provide a general overview of our research progress made in the past twelve months. Details on some of those research progress are immediately provided in subsequent sections. A list of publications resulting from AFOSR support is included at the end of this report.

II. Summary and Overview

Since the intended research program is for the white-light optical information processing and holography, attention gathering the optical components for use in such a processing system is necessary. The basic system involves white-light (Xenon and Zirconium arc lamps), incoherent (Mercury arc lamp) light sources, achromatic lenses, diffraction gratings, (amplitude or phase type), complex spatial filters and various supporting electro-optical elements. The basic systems of this white-light or incoherent light optical information processing system was synthesized during the earlier part of the first six month period, as shown in Fig. 1. Since the use of incoherent source for the processing, the physical processing environment is not as critical as coherent optical processor: For example, weighty optical bench is not required and it is not required to have completely dust free environment. This white-light optical processor greatly simplifies the stability and ruggedness of the pro-

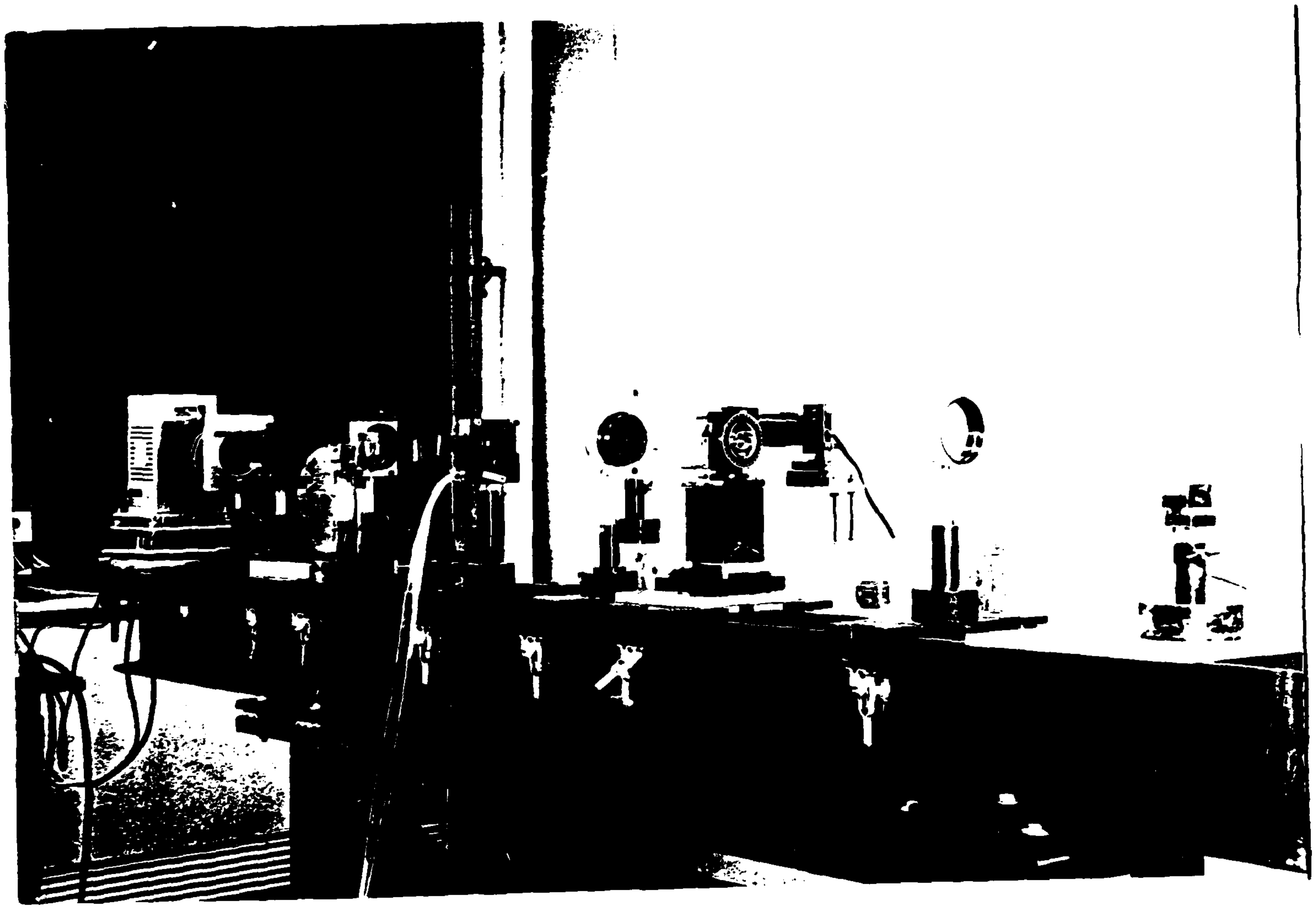


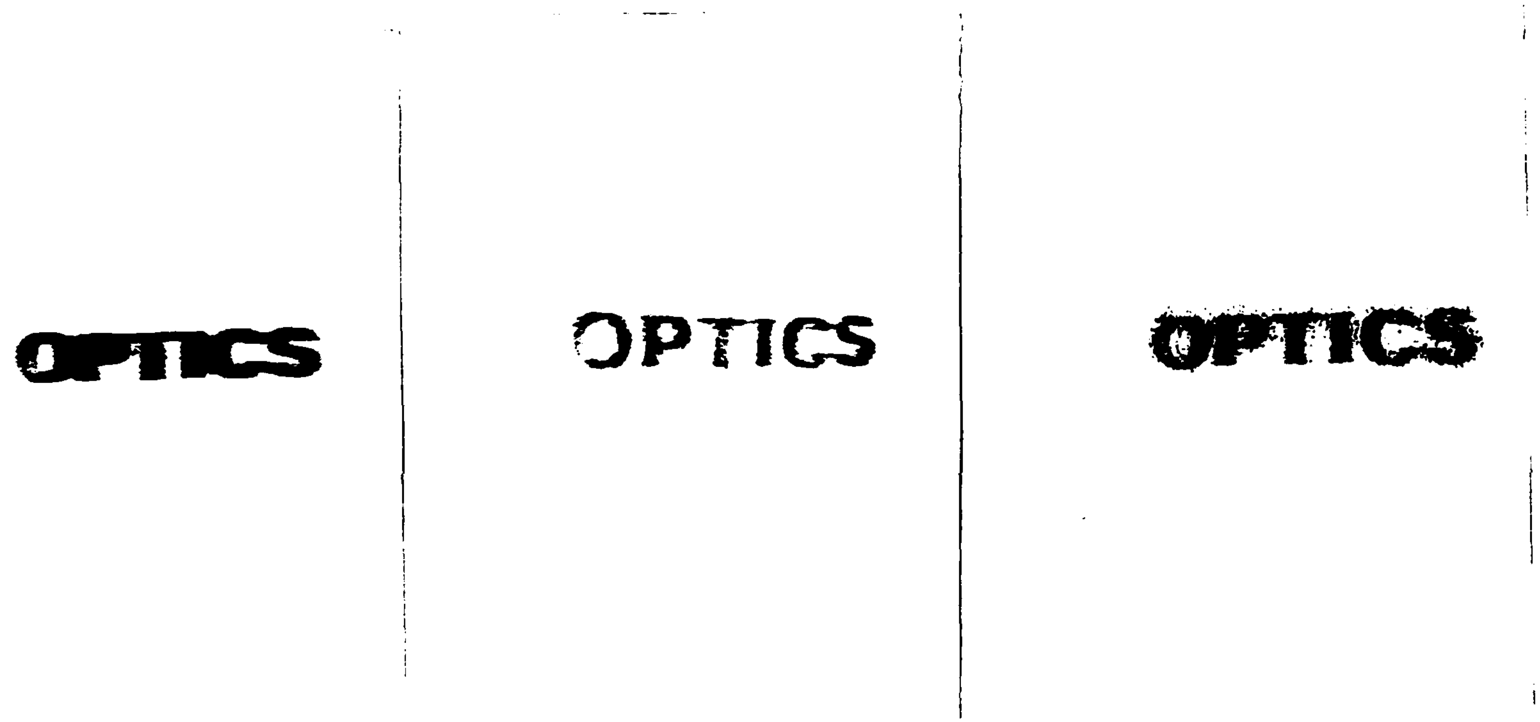
Figure 1. A White-Light Optical Processor

cessing system. Another interesting feature of this system is that the liquid gates are generally not required for the processing operation. Futhermore, because the use of broad spectral band white-light source, the system is particularly suitable for color image processing.

2.1 Smeared Image Deblurring (See Section III)

Our research in the past year period has included the smeared-photographic-image deblurring [1], sample of the result is shown in Fig. 2a. In comparison with the result obtained by coherent source, the one obtained with the white-light source offers a fewer artifact noise. However, the deblurring spatial filter that we used were a narrow spectral band centered at 5154Å green light. To compensate for the scaling of the signal spectrum due to the wavelength of the white-light source, a fan-shaped deblurring filter should be used. The generation of a fan shape deblurring filter by means of computer technique and optical coating technique will be reported in the future annual reports.

We have also extended this image deblurring technique to color photographic image deblurring [2], as shown in Fig. 3. We have pointed out earlier, the white-light processing technique is suitable for color image processing, the color image deblurring was achieved with narrow red and green color deblurring filters. The center wavelengths of this set of deblurring filters were about 6328Å and 5461Å respectively. The filter bandwidth contained five main lobes and thus spectral widths are about 100Å. From the result of Fig. 3, we see that the deblurring effect of the green letters "P" and "C" seems to be more effective than other color letters. This is primarily due to linear amplitude transmittance of these smeared letters. In other words, the smeared letters of red and yellow colors were more saturated.



a. Blurred Image

b. Deblurred With White-Light Technique

c. Deblurred With Coherent Technique

Figure 2. Linear-Photographic Image Deblurring

a. Blurred Color Image

b. Deblurred Color Image

Figure 3. Color Image Deblurring

We note that, the results of image deblurring were utilized narrow spatial filters in the spatial frequency plane. Extension to the whole spectral band of the white-light source on the aspect of the synthesis of a fan-shape spatial filter concept for image deblurring is the subject of current research that will be reported upon in the future annual reports.

2.2 Image Subtraction (See Section IV)

We have in the past year investigated the possibility of using incoherent and white-light sources for image subtraction. Since optical image subtraction is a one-dimensional processing operation, instead of using a point source of light, a line source can be utilized. Moreover, the image subtraction operates upon the one-to-one correspondent image points, a strictly broad coherence requirement is not needed. It is possible however to encode an extended incoherence source to obtain a point-pair spatial coherence function for the image subtraction operation [3-5] (see section V). In evaluating the spatial coherence requirement, we had applied the partially coherent theory. In experimental demonstration, we provide a set of continuous tone image transparencies as input objects as shown in Figs. 4a and 4b. By comparing these two figures, we see that a liquid gate was withdrawn from the optical bench in Fig. 4b. Figure 4c shows the subtracted image obtained with the incoherent source encoding technique, while Fig. 4d was obtained with coherent processing technique. From Fig. 4c, a profile of subtracted liquid gate can readily be seen, which from the result obtained with coherent source, the subtracted image is severely damaged by the coherent artifact noise. Thus we see that the incoherent technique is indeed offering a better image quality.

Figure a. The input objects.

Figure b. The input objects.

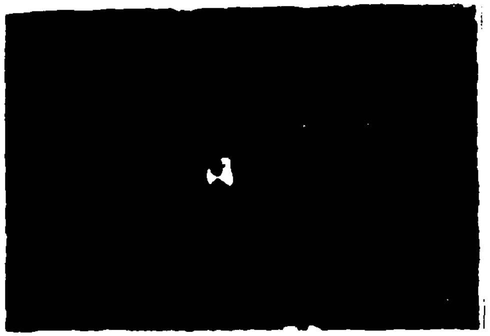


Figure c. Subtracted Image Obtained With Incoherent Technique.

Figure d. Obtained With Coherent Technique.

Figure 4. Incoherent Image Subtraction.

We have also extended this image subtraction technique for color images [6,7], as shown in Fig. 5. Fig. 5a and 5b shows two color images of a parking lot on input color transparencies. We note that a red color passenger car in Fig. 5a is missing in Fig. 5b. Figure 5c is the color subtracted image obtained with the incoherent source encoding technique. In this figure, a profile of red passenger car can clearly be seen at the output image plane. It is also interesting to see that the parking line (in yellow color) on the right side of the red car can readily be seen with the subtracted image.

Again, we note that, the results of image subtraction with encoded extended incoherent source were accomplished by narrow spectral band of light sources. Extensive additional research on the aspect of source encoding for extended white-light source is the subject of current research that will be reported upon in future annual reports.

2.3 Visualization of Phase Object (See Reference 8)

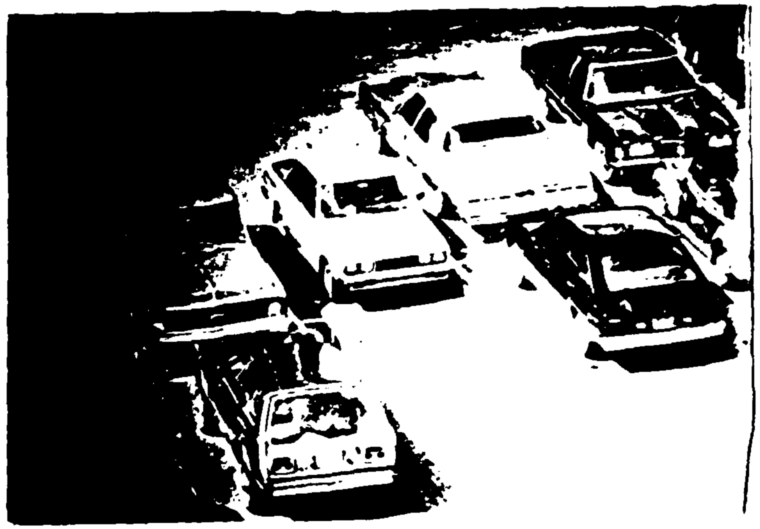
We have extended the color image subtraction technique for visualization [8] as shown in Fig. 6. By this variation of color coded fringe pattern, it is possible to determine the phase variation in more detail.

The detail analysis of this work will be reported in our next annual report.

2.4 Coherence Requirement (See Reference 9)

We have also in this period evaluated the coherence requirement for white-light optical processing [9]. The spatial and temporal coherence requirements for smeared image deblurring and image subtraction problems were evaluated. For image deblurring, we show that spatial coherence requirement is dependent upon the source slit

a. The input objects.



b. The input objects.

c. Subtracted Color Image.

Figure 5. Color Image Subtraction

Figure 6. Visualization of Color Coded Phase Object.

size, the smeared length, and the spatial frequency of the grating. For image subtraction, the spatial coherence requirement is dependent upon the ratio of slit size and the spacing of the slit of a source encoding mask, spectral bandwidth, and the separation of the input objects. From the obtained coherence requirements, we were able to develop a general source encoding concept for partially coherent optical processing [3].

The detail analysis of the coherence requirement will be reported in our next annual report.

2.5 Remarks

We have demonstrated experimentally white-light optical information processing technique utilizing a diffraction grating method. As compared with the conventional coherent optical processing technique, the white-light processing technique offers several basic advantages:

1. The cost of the processing system is significantly lowered with the elimination of the laser sources.
2. The alignment procedure of the white-light processing system is generally simpler than the coherent technique.
3. The output results are free from artifact noise that generally plagues the coherent processing systems.

In short, the white-light optical information processing system is simple, versatile and economical to operate. We would emphasize that, there are many information processing operations which can be carried out rather easily with a white-light source. In other words, if a high spatial coherent requirement (a requirement has to be evaluated) for an information processing operation is not needed, then a white-light processing technique will be more advantageous. However, if the demand of the spatial coherence for an information processing

operation is high, then coherent sources may not be avoided. We note that, the analysis of the cost and merit as a function of coherent requirement for the proposed white-light processing technique will be evaluated in our future research.

2.6 Future Research

Our future research is expected to follow the general direction addressed in the past year with a major attention given in the following:

1. We will synthesize a matched filter that is suitable for the white-light optical processing technique. Experimental demonstrations for the incoherent and the white-light processing technique will be carried out.
2. We will carry out a computer generated spatial filter program that is suitable for the broad spectral band optical processing program. In other words, a multiwavelength and multiband spatial filter may not be generated by coherence sources. However, to compensate the wavelength variation it is, in principle, to be generated by computer techniques.
3. We will carry out the experimental confirmations for those computer generated spatial filters for complex signal detection, image deblurring, image subtraction, color encoding problems, etc. for a broad band of white-light source.
4. We will investigate a source encoding technique for the image subtraction for broadband white-light source. Experimental confirmations will concurrently carry out for monochrome and color image subtraction.
5. Since the white-light source contains all the visible wavelength, we will develop a research program primarily devoted

to color image processing. We note that, initially all the visible images are color.

6. We will investigate the possibility of implementing natural sun light in the white-light optical processor. Experiments with the sun light processing technique will concurrent carry out. We expect interesting results will be obtained with the sun light source.
7. The analysis of the cost, merits, and limitations of the proposed white-light processing technique will be evaluated. With reference to the analysis, more sophisticated processing operation, as applied to wide-band signal and digital signal processings will be carried out.
8. We will investigate the possibility of developing a real-time white-light optical processor. This real-time processor should have the capability of performing the major optical processing operations that a coherent processor can provide. We will also investigate the possible application of the white-light and sun light processing technique to some problems in optical computing (e.g., digital or analog).
9. We would also investigate various possible applications of the white-light optical signal processing for tracking and identification of aircrafts and missiles; spread spectrum communications; counterfeit deterrence; acoutical-optical sonic spectral analysis, and recognition; aerial and satellite picture processing, enhancement and identification; and application to various biological and medical aspects.

In short, our goal is to develop a full research program on the white-light signal processing technique which has the capability of

carrying out major processing operations that a coherent optical processor can offer. This white-light optical processing system is potentially important in many areas of monochrome and color signal processings. We stress that this white-light processing technique will provide a first step toward the research and development of white-light and sun-light optical computers. We note that, if the demand of the spatial coherent requirement for an information processing operation is not stringent (which will be determined in our future research program), then the white-light signal processing technique is more convenient and reliable than the conventional coherent optical processing techniques. However, if the spatial coherent requirement becomes very stringent, then the use of a coherent source may not be avoided.

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SECTION III

White-Light Optical Information Processing

Optical processing of photographic images

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Abstract. Recent advances in electro-optics have brought into use communication and information theory to analyze performance in coherent and incoherent optical information processing systems. An optical information processsing system can be analyzed with many of the same concepts of linear system theory (e.g., spatial impulse response, spatial frequency and spatial domain synthesis, etc.), and the photographic images to be processed can be regarded in the same manner as time signals (e.g. spatial frequency content, spatial amplitude and phase modulation, space-bandwidth product, etc.). Both coherent and incoherent optical processing systems can be treated as linear systems, and the processing operation can generally be carried out by communication theory concepts.

Although coherent optical information processing operations have been used for performing complex amplitude operations, complex processing can also be performed with incoherent or white-light illumination. The importance of optical information processing operations, either coherent or incoherent, is due to the basic Fourier transform properties of lenses. In this paper, we will discuss mostly the incoherent systems because they are of more recent interest and possess certain advantages, we feel, over the traditional coherent optical processors. Experimental illustrations of the results are provided.

In view of the broad area in optical processing of photographic images, we will confine ourselves to a few applications that we consider of general interest. We apologize for the omission of other techniques and applications, and for neglecting the inclusion of their references.

Keywords: photo-optical instrumentation engineering; photographic images; coherent optics; optical image processing.

Optical Engineering 20(5), 666-676 (September/October 1981)

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1. INTRODUCTION

Communication and information theory was originated by a group of mathematically oriented electrical engineers whose interest was centered on electrical communication. Nevertheless, from the very beginning of this discovery of communication and information theory, interest in its application to optical systems has been vigorous. As a result of recent advances in optical signal processing and optical communications, the relationship between optics and communication theory has grown very rapidly.

Mention must be made of a few important early contributions to this field. It was in the early 1950s that the communication and information theory aspects of optical processing techniques first became evident. The most important impact must be due to Gabor's work on light and information[1] in 1951; Elias, Grey, and Robinson's work on Fourier treatment of optical processes[2] in 1952; Elias's paper on optics and communication theory[3] in 1955; and Toraldo di Francia's work on resolving power and information[4] in 1955. However, the very first application of communication theory to modern optical information processing was probably O'Neill's work on spatial filtering in optics[5] in 1956. Because of the broad interest in this field at that time, a special symposium, Communication and Information Theory Aspect of Modern Optics,[6] took place in 1960. Since then, the application of communication and information theory to optical signal processing has commanded great interest. The applications of optical spatial filtering were particularly evident in the field of radar signal processing, and it was in this field that Cutrona, Leith, Palermo, and Porcello published a classic article on optical data processing and filtering systems[7] in 1960. This article stimulated a broad interest in optical processing of photographic images. With the invention of a strong coherent source, i.e., laser, in the early 1960s, Leith and Upatnieks' work on reconstructed wavefront and communication theory[8] allowed for the first time the formation of high quality holographic images. Using the spatial frequency carrier concept of Leith and Upatnieks for holography, the 1964 paper "Signal Selection by Complex Spatial Filtering" by VanderLugt[9] introduced the subject of optical character recognition via the optical matched filter correlator. Since then optical information processing has been applied to a large variety of problems. Therefore, it is

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evident that communication and information theory has stimulated a broad range of application to modern optical information processing.

Coherent optical information processing operations have traditionally been regarded as the most useful for performing complex amplitude operations. However, in recent years complex information processing performed with incoherent or white-light illumination has received increased attention. Nevertheless, the importance of optical information processing operations, either coherent or incoherent, is primarily based on the basic Fourier transform property of lenses. The applications of these two optical processing systems to photographic images will be described. Experimental illustrations of the results will be provided.

In view of the broad area in optical processing of photographic images and the confines of space, we will discuss a few applications that we consider of general interest. The field has now matured to the point where there are many good textbooks available, and we refer the general reader to several of these.[10-13]

2. INCOHERENT OPTICAL PROCESSING SYSTEMS

The use of coherent light enables optical systems to carry out many sophisticated information processing operations.[14] However, coherent optical processing systems are plagued with coherent artifact noise, which frequently limits the processing capability of the systems. Although many optical information processing operations can be implemented by systems that use incoherent light,[15,16] there are other serious problems. On one hand, the incoherent processing system is capable of reducing the inevitable artifact noise, but on the other hand it generally introduces a dc-bias buildup problem, which again can result in poor noise performance. There are, however, techniques which have been developed for coherent operation with light of reduced coherence[17,18] or noise averaging,[19,20] but at the expense of increased system complexity.

Attempts at reducing the temporal coherence requirements on the light source in the optical information processing fall into two general categories: (1) the use of incoherent instead of coherent optical processing pursued by Lowenthal and Chavel[21] and Lohmann,[22] among others; and (2) the reduction of coherence while still operating with linear-in-amplitude systems pursued by Leith and Roth.[23] The latter is the one that we believe to be a very promising technique, and it is the concept that Yu is pursuing.

Since its invention the laser has become a useful tool for many applications in coherent optical information processing. This trend of advances was mainly due to the complex amplitude processing capability. In addition to the noise problem mentioned above, the coherent sources are usually more expensive and the system stability is usually critical.

Recently, in looking at optical information processing techniques from a different viewpoint, a question arose: Is it necessary that all the information processing operations require a coherent source? We found that there are several optical information processing operations that can be carried out with reduced coherence. If the coherence requirement for certain information processing operations is not too high, it may be carried out with incoherent or white-light sources. In this section we will describe a white-light processing technique by which photographic images can be processed with complex amplitude filters. We note that this white-light processor may alleviate the major disadvantages imposed on the coherent processing system.

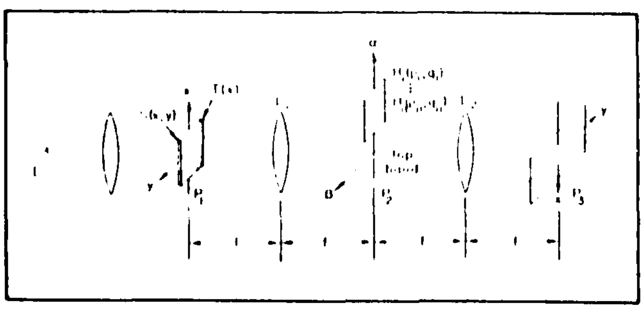

Fig. 1. A white-light optical processor. I, white-light source; T(x), phase grating; L, achromatic lens; H(p,q), complex spatial filters.

Now we describe a photographic image processing technique that can be carried out by a white-light source,[24,25] as shown in Fig. 1. We note that the white-light processing system is similar to that of a coherent processing system except that a white-light source and a high diffraction efficiency grating are inserted in the input plane P_1. If we place a photographic transparency $s(x,y)$ in contact with the diffraction grating, then the complex light field for every wavelength λ behind the transform lens L_1 is

$$E(p,q;\lambda) = C\iint s(x,y)\left[1+\cos(p_0 x)\right] \exp\left[-i(px+qy)\right]dxdy \;, \tag{1}$$

where the integral is over the spatial domain of the input plane P_1, (p,q) denotes the angular spatial frequency coordinate system, and C is a complex constant.

For simplicity of analysis, we drop the proportionality constant, and Eq. (1) becomes

$$E(p,q;\lambda) = S(p,q) + S(p-p_0,q) + S(p+p_0,q) \;, \tag{2}$$

where $s(p,q)$ is the Fourier spectrum of $s(x,y)$,

$$p = \frac{2\pi}{\lambda f}\alpha$$

and

$$q = \frac{2\pi}{\lambda f}\beta \;.$$

(α,β) is the linear spatial coordinate system of (p,q) and f is the focal length of the achromatic transform lens L1. In terms of the spatial coordinates of α and β, Eq. (2) can be written,

$$E(\alpha,\beta;\lambda) = C_1 S(\alpha,\beta) + C_2 S\left(\alpha - \frac{\lambda f}{2\pi}p_0,\beta\right) + C_3 S\left(\alpha + \frac{\lambda f}{2\pi}p_0,\beta\right) \;. \tag{3}$$

From the above equation, we see that two first-order signal spectral bands (i.e., second and third terms) are dispersed into rainbow colors along the α axis, and each spectrum is centered at $\alpha = \pm(\lambda f/2\pi)p_0$.

In the analysis we assume that a sequence of complex spatial filters for various λ_n is available, i.e., $H(p_n,q_n)$, where

$$p_n = \frac{2\pi}{\lambda_n f}\alpha$$

and

$$q_n = \frac{2\pi}{\lambda_n f}\beta \;.$$

If we place these complex spatial filters in the spatial frequency plane with each centered at $\alpha = (\lambda_n f/2\pi)p_0$, then the complex light field behind the spatial frequency plane is

$$E(p,q;\lambda) = S(p-p_0,q)\sum_{n=1}^{N} H(p_n-p_0,q_n) \;. \tag{4}$$

The corresponding complex light distribution at the output plane P_1 of the processor for each λ would be

$$g(x,y;\lambda) = \sum_{n=1}^{N} \iint S(p - p_n, q)\, H(p_n - p_n, q_n) \exp\left[i(p_n x + q_n y)\right] dp_n\, dq_n \;, \tag{5}$$

where the integration is over the spatial domain. We assume that the signal spectrum is spatial frequency limited and the bandwidth of $H(p_n, q_n)$ extended to this limit, i.e.,

$$\hat{H}(p_n, q_n) = \begin{cases} H(p_n, q_n), & \alpha_1 < \alpha < \alpha_2 \;, \\ 0, & \text{otherwise} \;, \end{cases} \tag{6}$$

where $\alpha_1 = (\lambda_n f / 2\pi)(p_0 + \Delta p)$, and $\alpha_2 = (\lambda_n f / 2\pi)(p_0 - \Delta p)$ are the upper and the lower spatial limits of $\hat{H}(p_n, q_n)$, and Δp is the bandwidth of the input signal. The limiting wavelengths of the dispersed spectra at the upper and the lower edges of the filters are,[26]

$$\lambda_\ell = \lambda_n \frac{p_0 + \Delta p}{p_0 - \Delta p}$$

and

$$\lambda_h = \lambda_n \frac{p_0 - \Delta p}{p_0 + \Delta p} \;, \tag{7}$$

and the corresponding wavelength spread over the filters is, therefore,

$$\Delta\lambda_n = \lambda_n \frac{4 p_0 \Delta p}{p_0^2 - (\Delta p)^2} \;. \tag{8}$$

If the spatial frequency p_0 of the grating is high, then the wavelength spread over the filters can be approximated,

$$\Delta\lambda_n \simeq \frac{4\Delta p}{p_0} \lambda_n, \quad p_0 \gg \Delta p \;. \tag{9}$$

Since the complex spatial filterings take place in discrete Fourier spectral bands of the light source, the filtered signals are *mutually* incoherent. Therefore the output light intensity distribution is

$$I(x,y) = \sum_{n=1}^{N} \Delta\lambda_n |g(x,y;\lambda_n)|^2$$

$$= \sum_{n=1}^{N} \Delta\lambda_n |s(x,y;\lambda_n) * h(x,y;\lambda_n)|^2 \;, \tag{10}$$

where $h(x,y;\lambda_n)$ is the spatial impulse response of the filter $H(p_n, q_n)$, and $*$ denotes the convolution operation. From the above equation, we see that the white-light processing technique is indeed capable of processing the signal in complex amplitude. Since the output intensity is the sum of the mutually incoherent narrow-band irradiances, the annoying coherent artifact noise can be suppressed.

In addition, the white-light source contains all the visible wavelengths of the electromagnetic wave, and therefore is particularly suitable for color image processing. We further note that the white-light processor of Fig. 1 can also be used for coherent and partial coherent light.

3. PHOTOGRAPHIC IMAGE DEBLURRING

One of the interesting applications of optical information processing is restoration of blurred photographic images. The deblurring that we will describe is an inverse complex spatial filtering process. We consider the Fourier spectrum of a blurred photographic image as

$$F(p,q) = S(p,q)\, D(p,q) \;, \tag{11}$$

where $S(p,q)$ is the Fourier spectrum of unblurred image and $D(p,q)$ is the Fourier spectrum of the blur function.

In deblurring, we apply the blurred photographic image $f(x,y)$ to a prescribed inverse filter, as shown in Fig. 2. We let the inverse filter function be

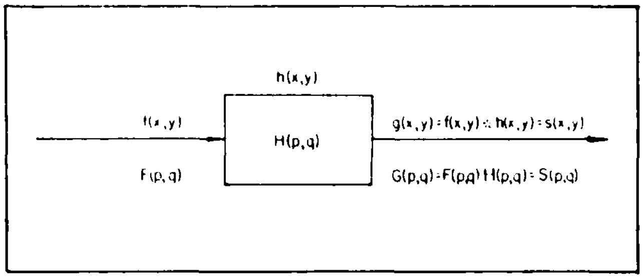

Fig. 2. Block diagram of an image deblurring system. (x,y), spatial domain. (p,q), spatial frequency domain.

$$H(p,q) = \frac{1}{D(p,q)} \;, \tag{12}$$

then the output Fourier spectrum is

$$G(p,q) = F(p,q)\, H(p,q) = S(p,q) \;, \tag{13}$$

which is essentially the Fourier spectrum of the unblurred image. The inverse transform is

$$g(x,y) = \iint f(x',y')\, h(x - x', y - y')\, dx'dy' = s(x,y) \;, \tag{14}$$

which is the unblurred image $s(x,y)$.

We note that photographic image deblurring by coherent optical processing technique was illustrated by Tsujiuchi[27] in 1963. The inverse spatial filter was synthesized by the combination of an amplitude and a pure phase filter. This can also be accomplished by a holographic synthesis technique. The preparation of such a phase filter by holographic technique had been studied by Stroke and Zech,[28] and by Lohmann and Paris.[29] Nevertheless, the holographic synthesis technique also suffers one disadvantage, namely a low diffraction efficiency. Mention must also be made of the image deblurring with computer-generated phase filter obtained by Tsujiuchi, Honda, and Fukaya.[30] They had shown various effects due to amplitude, phase, and amplitude-phase filterings. Another interesting result obtained by Horner[31,32] should also be mentioned. He has shown that optimum image deblurring may be obtained with least mean-square-error filtering.

We will briefly describe the synthesis of a phase filter that, when combined with an amplitude filter, can be used for image deblurring. For example, let the amplitude transmittance of a linear smeared point image be

$$f(y) = \begin{cases} 1, & -\frac{1}{2}\Delta y \le y \le \frac{1}{2}\Delta y \;, \\ 0, & \text{otherwise} \;, \end{cases} \tag{15}$$

where Δy is the smear length. If the blurred image is inserted in the input plane P_1 of a coherent optical processor of Fig. 1, the complex light field on the spatial frequency plane would be

$$F(q) = \Delta y \, \frac{\sin(q\Delta y/2)}{q\Delta y/2} \, , \tag{16}$$

the familiar sinc function. In principle, the blurred image may be deblurred by inverse filtering. To do so we let the filter be a combination of an amplitude and a phase filter, as shown in Fig. 3. The filter

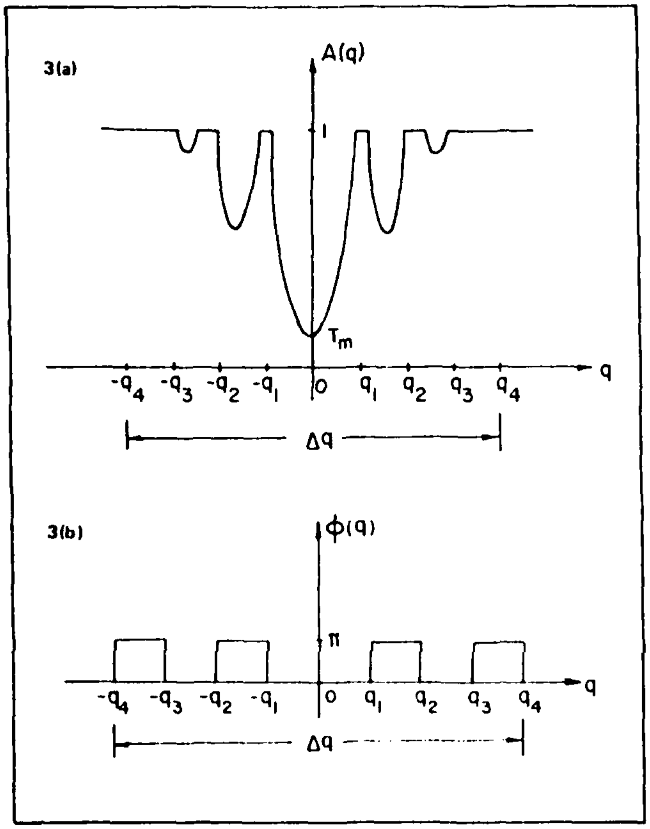

Fig. 3. Inverse spatial filter for deblurring a linearly smeared image. (a) Amplitude filter function, and (b) phase filter function

transfer function is

$$H(q) = A(q)\exp[i\phi(q)] \, . \tag{17}$$

We let T_m be the minimum transmittance of the amplitude filter and the relative degree of restoration[10,11] is defined as

$$D = \frac{1}{T_m \Delta q}\int \frac{F(q)H(q)}{\Delta y}\, dq \times 100\% \, , \tag{18}$$

where Δq is the spatial bandwidth of the filter. We note that perfect restoration is unattainable, since it requires that T_m approaches zero. There is also another shortcoming for lower T_m; it would result in a lower signal-to-noise ratio. By taking the account of film grain noise, a minimum value of T_m with a fairly good signal to noise ratio may be attained.

We now assume that the phase filter is a holographic type; that is,

$$T(q) = \frac{1}{2}\left\{1 + \cos\left[\phi(q) + y_0 q\right]\right\} \, , \tag{19}$$

where y_0 is an arbitrary constant. Then the filtered Fourier spectrum is

$$G(q) = \frac{1}{2}F(q)A(q) + \frac{1}{4}\left[F(q)H(q)\exp(iy_0 q) + F(q)H^*(q)\exp(-iy_0 q)\right] \tag{20}$$

It is clear that the first term is the spectrum due to the amplitude filter alone, which will be diffracted on the optical axis at the output plane P_3 of Fig. 1. The second and third terms are the restored Fourier spectra, in which the restored images will be respectively diffracted around $y = y_0$ and $y = -y_0$ at the output plane P_3.

An interesting alternative approach related to holographic synthesis of the filter has recently been reported by Vasu and Rogers.[14]

We now briefly describe a white-light-processing technique for smeared-image deblurring. We place a smeared-image transparency in contact with a sinusoidal phase grating at the input plane P_1 of the white-light processor of Fig. 1. The mathematics of this have already been described in Sec. 2. For simplicity, we assume that the input transparency is spatial frequency limited and that the smearing is in the y direction of the input spatial plane. We further assume that a narrow-band deblurring filter, for a given wavelength λ_0 as described earlier, is provided.

If we insert the deblurring filter of $H(\beta)$ over a narrow spectral band of the smeared-signal spectra $F[\alpha - (\lambda f/2\pi)p_0, \beta]$ at $\lambda = \lambda_0$, then the complex light field at the output plane P_3, for a given wavelength λ over the deblurring filter, can be evaluated by the following integral equation:

$$g(x,y;\lambda) = C\int_{-\infty}^{\infty}\int_{\alpha_1}^{\alpha_2} F\left(\alpha - \frac{\lambda f}{2\pi}p_0, \beta\right) H(\beta) \cdot \exp\left[i\frac{2\pi}{\lambda f}(\alpha x + \beta y)\right] d\alpha\, d\beta \, , \tag{21}$$

where C is a complex constant and $H(\beta)$ is the deblurring filter. The corresponding output-light intensity distribution can be approximated by

$$I(x,y) = \int_{\Delta\lambda} |g(x,y;\lambda)|^2 d\lambda \simeq K\,\Delta\lambda |f(x,y)\exp(ip_0 x) * h(y)|^2 \, , \tag{22}$$

where $\Delta\lambda = \lambda_0(4\Delta p/p_0)$ is the narrow spectral band of light over the deblurring filter, $h(y)$ is the spatial impulse response of $H(\beta)$, $*$ denotes the convolution operation, and K is a proportionality constant. From the above equation, we see that the filtered image is diffracted around the optical axis at the output image plane P_3.

As an experimental illustration, Fig. 4(a), shows the linear-

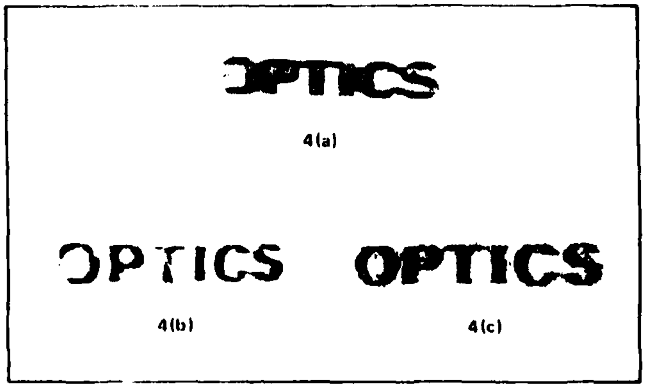

Fig. 4. Linearly smeared image deblurring. (a) Smeared object, (b) deblurred with white light technique, and (c) deblurred with coherent light (Zhuang, Chao, Yu, 1981[15]).

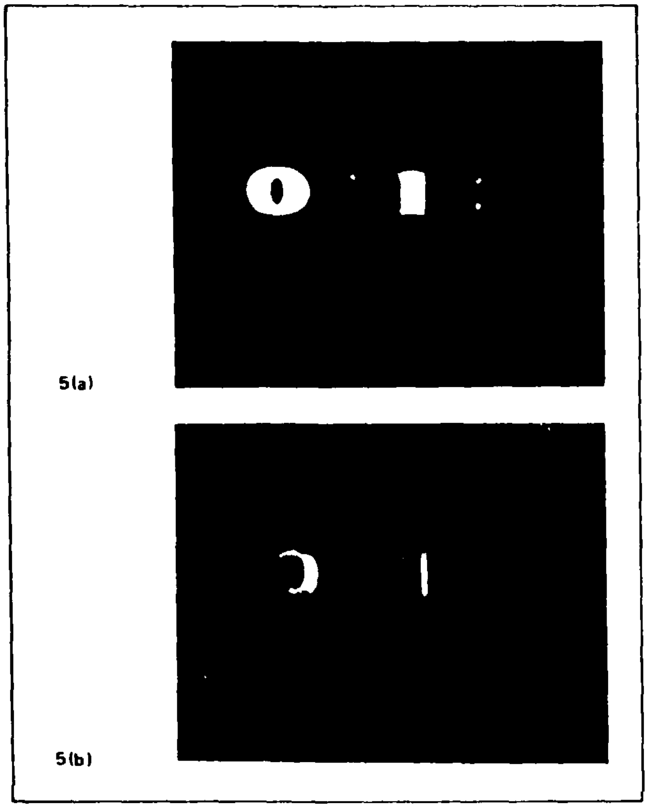

Fig 5 Smeared image deblurring in color (a) Blurred image and (b) deblurred with white light technique (Yu, Zhuang, and Chao, to be published[16]).

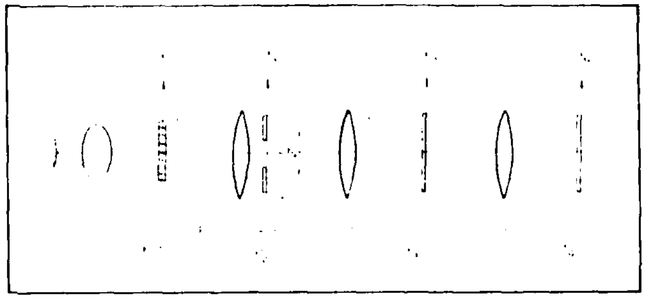

Fig. 6. Image subtraction with encoded extended incoherent source. MS, multiple slit; P2, input plane; P3, filter plane, P4, output plane, L1, L2, L3, convergent achromatic lenses of focal length F (Wu, Yu, to be published[44]).

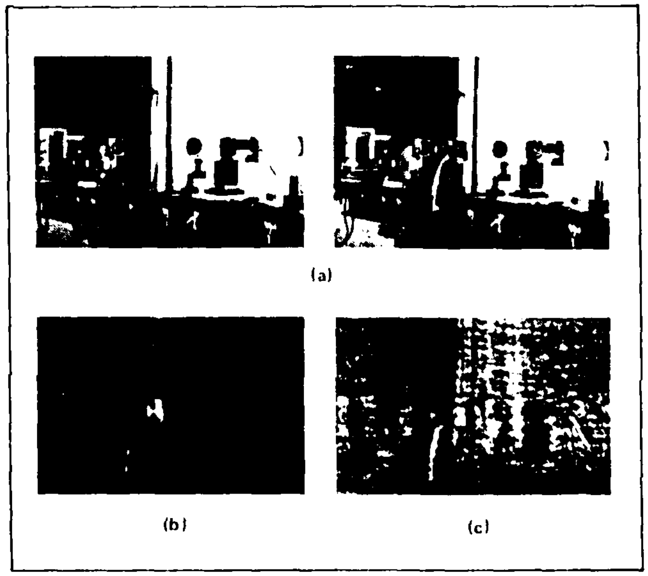

Fig. 7. Image subtraction. (a) Input objects, (b) output with incoherent technique, and (c) output with coherent technique (Wu, Yu, to be published [44]).

smeared photographic image of a word *optics* as a blurred object. Figure 4(b) shows the deblurred image obtained with the white-light-processing technique, and Fig. 4(c) shows the result obtained with the coherent-processing technique. Explicit details are given in Ref. 35. From these results, we see that the artifact noise was substantially reduced with the white-light-processing technique. The deblurred image obtained with the coherent technique appears to be sharper than the one obtained with the white-light technique because of the high spatial coherence of the light source. However, the drawback can be overcome if one uses a smaller white-light source (i.e., a pinhole) and a broad-spectral-band deblurring filter to cover the entire smeared signal spectrum. Design of such a broad band fan shaped filter is under investigation.

Since the white-light source contains all visible wavelengths of the spectrum, the white-light process is suitable for color image deblurring.[16] Let us place a smeared color photographic image at the input plane P_1 of the white-light processor of Fig. 1. At the spatial frequency plane P_2, two sets of Fourier spectra are smeared in rainbow colors. In color image deblurring, we place three primary color (i.e., red, green, and blue) narrow-spectral-band deblurring filters in the appropriate locations in the spatial frequency plane. Since the deblurred images from each of the primary color filters are mutually incoherent, the output image irradiance will be

$$I(x,y) = \Delta\lambda\Big[|g(x,y;\lambda_r)|^2 + |g(x,y;\lambda_g)|^2 + |g(x,y;\lambda_b)|^2\Big] , \tag{23}$$

where $\Delta\lambda$ is the narrow spectral band of the deblurring filter; $g(x,y;\lambda)$ is the deblurred image, and λ_r, λ_g, and λ_b are the red, green, and blue primary color wavelengths.

For an experimental illustration, a linear-smeared color photographic image of a word "optics" is shown in Fig. 5(a). The deblurred color image obtained with the white-light technique is shown in Fig. 5(b). Strictly speaking, a fan-shaped deblurring filter over the entire smeared color Fourier spectra should be used. Such a filter is under investigation.

4. PHOTOGRAPHIC IMAGE SUBTRACTION

Another interesting application of optical photographic image processing is image subtraction. Image subtraction may be of value in many applications such as urban development, highway planning, earth resources studies, remote sensing, meteorology, automatic surveillance, inspection, etc. Optical image subtraction may also be applied to communications. As a means of bandwidth compression, for example, it would be necessary to transmit only the differences between images in successive cycles, rather than the entire image in each cycle.

Optical-image synthesis by complex amplitude subtraction was described by Gabor et al.[illegible] The technique involves successive recordings of two or more complex diffraction patterns on a holographic plate and the subsequent reproduction of the composite hologram images. A few years later, *Bromley et al.*[illegible] *described a holographic* Fourier subtraction technique, for which a real-time image and a previously recorded hologram image can be subtracted. Although good image subtraction by their experiments was reported, it

appears that the illumination for the holographic image reconstruction must be arranged carefully. In a more recent paper, Lee et al.[?] proposed a technique that showed that image subtraction and addition can also be achieved by a diffraction grating technique. This technique needs the insertion of a diffraction grating in the spatial frequency domain of the coherent optical processor. We note that the advantage of this technique is a real time subtraction capability.

Since space does not permit us to review all the various techniques of image subtraction, we refer the reader to the review paper by Ebersole.[?] However, most of the optical image synthesis involved a coherent source to carry out the image subtraction. But coherent sources also introduce artifact noise which frequently limits the processing technique, as described in the previous section, to image subtraction.[?]

We will now insert two photographic image transparencies in contact with phase grating at the input plane P_1 of a white light optical processor of Fig. 1. At the spatial frequency plane P_2, the complex light distribution for each wavelength λ of the light source may be described, as

$$E(p,q;\lambda) = S_1(p - p_0, q)\exp(-i\beta_0 q)$$

$$+ S_2(p - p_0, q)\exp(i\beta_0 q)\,, \qquad (24)$$

where $S_1(p,q)$ and $S_2(p,q)$ are the Fourier spectra of the input signals $s_1(x,y)$ and $s_2(x,y)$ respectively, and β_0 is an arbitrary constant. Again we see that two input signal spectra disperse into rainbow colors along the α axis of the spatial frequency plane.

In image subtraction, we insert a diffraction grating in the spatial frequency plane. Since the dispersed Fourier spectra varies with respect to the wavelength of the light source, we would insert a fan shaped grating to compensate the wavelength variation. We let this fan shaped grating be

$$H(q) = [1 + \sin\beta_0 q] \qquad (25)$$

and the output diffraction can be shown as

$$g(x,y) = \Delta\lambda\Big\{s_1(x,y - \beta_0) - s_2(x,y + \beta_0)$$

$$+ (1/2)\big[s_1(x,y) - s_2(x,y)$$

$$s_1(x,y - 2\beta_0) + s_2(x,y + 2\beta_0)\big]\Big\}$$

$$\exp(ip_0 x) \qquad (26)$$

Thus, the subtraction of the two input signals $\big[s_1(x,y) - s_2(x,y)\big]\exp(ip_0 x)$ can be seen at the optical axis of the output plane. We point out that, in practice, it is difficult to obtain a white light point source. However, this shortcoming can be overcome with a source encoding technique that we will describe.[?]

Since image subtraction is a one dimensional (1-D) processing operation, instead of a point source of light, a line source of light perpendicular to the direction of the two images can be utilized. In addition, the coherence requirement for image subtraction is only for

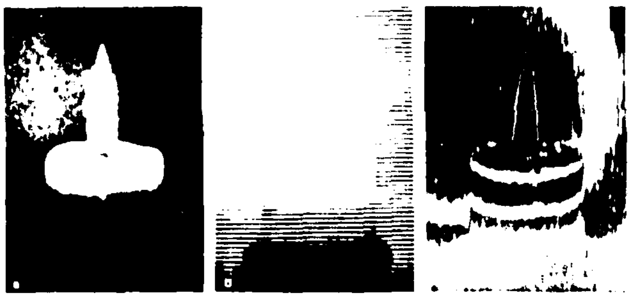

Fig. 8. Isophotes linearly spaced in log intensity. (a) Original image, (b) halftone image, and (c) isophot image (Strand, 1975[?]).

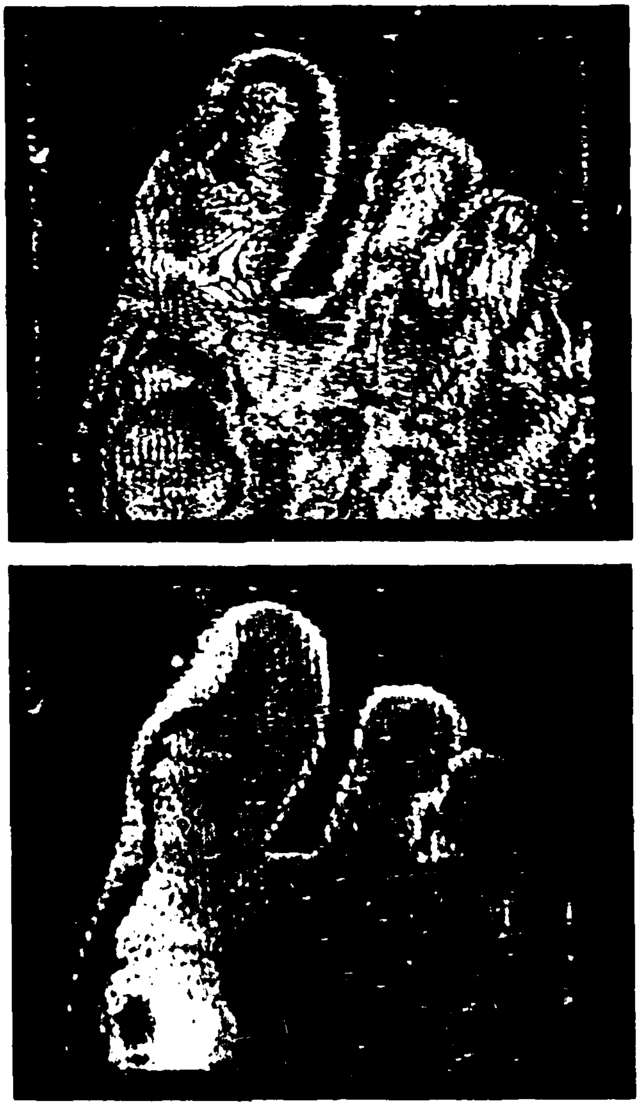

Fig. 9. Pseudocolor encoding with halftone screen. (a) Obtained with coherent source and (b) obtained with white light source (Tai, Yu and Chen, 1978[?]).

every point pair between the two images, and a strict coherence requirement is not needed. In other words, it is possible to encode an extended incoherent source to achieve the point pair coherence requirement. To do so, we apply the Van Cittert-Zernike's theorem.[?] A point-pair coherent function can be determined. As a result one can encode an extended incoherent source with a multislit mask. With reference to Fig. 6, the coherent function at the input plane P_1 is

$$\mu(x_1 - x_2) = \frac{\sin\left(2N\pi\dfrac{x_1 - x_2}{2h_0}\right)}{N\sin\left(2\pi\dfrac{x_1 - x_2}{2h_0}\right)}\;\frac{\sin\left[2\pi\dfrac{s(x_1 - x_2)}{h_0 d}\right]}{2\pi\dfrac{s(x_1 - x_2)}{h_0 d}} \qquad (27)$$

where d is the spacing of the slits, s is the slit width, and N is the total number of slits over the extended source. The degree of spatial coherence for each pair of points separated by a distance $2h_0$ is therefore

$$\mu(2h_0) = \mathrm{Sinc}\,\frac{2\pi s}{d} \tag{28}$$

From the above equation, if

$$\frac{s}{d} \ll 1,$$

a high degree of point-pair coherence can be achieved. In comparison with a single slit case, the intensity of the output image can be increased N fold. In other words, the source encoding provides an efficient utilization of the light source.

In our experimental demonstration, a multislit mask with a 25 μm spacing and 2.5 μm width was adopted for the source encoding. The light source was a mercury arc lamp with a green filter. Figure 7(a) shows two image transparencies as input objects. Figure 7(b) shows the subtracted image obtained with the incoherent technique. In comparison, we also provide the subtracted image obtained with the coherent technique as shown in Fig. 7(c). From the results, we see that the one obtained with the incoherent technique offers better image quality and less artifact noise.

Finally, we would stress that the source encoding may be extended to white light processing technique and a program is currently under way to investigate this.

5. NONLINEAR PROCESSING OF PHOTOGRAPHIC IMAGES

So far in previous sections we have discussed linear spatial-invariant operations. There are, however, techniques available for nonlinear processing operations. One such approach is an optical homomorphic filtering system which has been quite successfully applied using digital techniques. Recently, Kato and Goodman proposed nonlinear processing of photographic images with a coherent optical system using halftone screen processes. The extension of Kato and Goodman's halftone screen technique to nonmonotonic and monotonic nonlinear image processing was subsequently pursued by Sawchuk and Dashell,[50] Strand, as shown in Fig. 8, and Liu, Goodman, and Chan. Application of the halftone screen techniques for pseudocolor encoding of monotone images with coherent optical processing was also reported by Liu and Goodman and with an incoherent source by Tai, Yu, and Chen as shown in Fig. 9.

We note one major limitation with the halftone screening technique; the spatial resolution of the photographic image is limited by the halftone screen itself, which is generally several orders of magnitude lower than the photographic film. It might be possible to produce a halftone picture with resolution up to 100 ℓ/mm using a computer-driven writer but the process would be complex and costly.

The nonlinear processing technique can also be achieved with a Fabry-Perot interferometric method as reported by Bartholomew and Lee,[57] and with the utilization of film nonlinearity reported by Tai, Cheng, and Yu.[58] Mention must be made that real-time nonlinear processing of photographic images with liquid crystal valves is currently being pursued by Michaelson and Sawchuk, and by Soffer et al.[59]

It is possible to use the inherent film nonlinearity to perform logarithmic and exponential transformations. Using the basic H-D curves of various films, carefully choosing the appropriate γ and using two step contact printing, Yu achieved a logarithmic amplitude transmittance for an input exposure range of 50. The inverse transformation of the filtered logarithmic signal can also be performed using a two-step approach. The details and specific films used can be found in Ref. 59.

Finally, we note that there is an interesting technique of photographic dynamic range compression proposed by Mueller and Caulfield. They have shown that ordinary photographic emulsions can record information of high dynamic range that we usually do not recognize. They used a surface relief technique that has little effect on the d.c. and low spatial frequency contents of the photographic image. The relief pattern is more like a spatial gradient of the recorded density pattern, such that the surface has the greatest relief where the spatial density pattern changes most rapidly. Although the relief images were not readily observed with diffuse illumination, using a novel incoherent processing technique they were able to show a wide dynamic range of the photographic image as depicted in Fig. 10. The technique was applied by blocking the d.c. component in the Fourier plane of the retroreflected light from the relief surface of the photographic film.

6. SPACE-VARIANT PROCESSING OF PHOTOGRAPHIC IMAGES

In the previous sections we have discussed only the space-invariant processing operation of photographic images. In other words, each image point to be processed is affected by the same processing operation. Although the space-variant processing concept has been known and successfully applied in system theory and digital processing techniques, the application of this concept to optical processing


10(a)

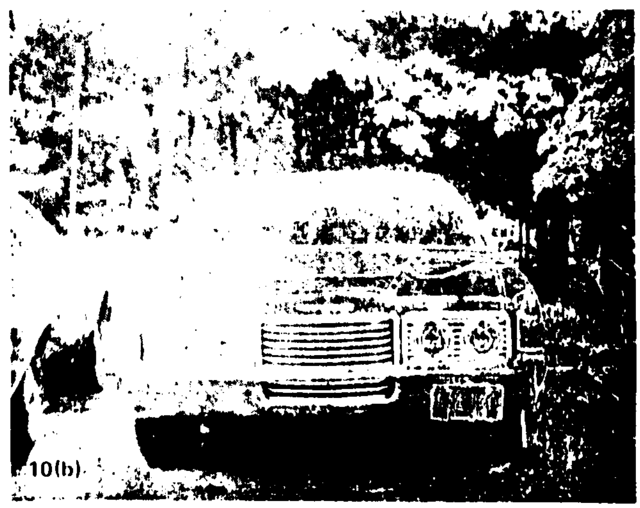
10(b)

Fig. 10. Dynamic range expansion. (a) Overexposed photograph and (b) bright field retrieval from the relief image of the original negative (Mueller and Caulfield, 1980[60])

is relatively recent. In 1965, Cutrona[62] proposed a general optical space-variant processing concept, analogous to the Fourier-transform technique, in terms of system eigenfunctions. The technique is, however, of only theoretical interest, since it is not known how to find the set of eigenfunctions. Attempts had been made by Heinz, Artman, and Lee in optical space-variant processing, using matrix multiplication. Some calculated results were reported in their paper. In a recent article, Deen, Walkup, and Hagler[64] reported a space-variant operation using volume holograms. The most graphic example of space-variant processing is the geometric transformation by Bryngdahl,[65] who used a computer-generated *hologram* for the operation. Mention must also be made of Sawchuk's work,[66] using the computer technique of space-variant image restoration by coordinate transformation.

We will now describe a basic concept to achieve optical space-variant processing similar to that of homomophic processing illustrated in the previous section. A general space-variant system may be described by a block diagram, as shown in Fig. 11(a). The input-

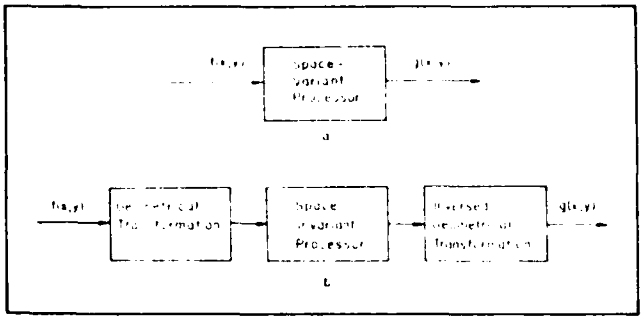

Fig. 11. Block diagram of space-variant processor, showing nomenclature

output relation may be described

$$g(x,y) = \iint h(x,y;x'y')\,f(x',y')\,dx'dy' , \tag{29}$$

where $h(x,y;x'y')$ is the space-variant impulse response. Needless to say, if $h(x,y;x'y')$ is described as a function of the coordinate difference, i.e., $h(x-x', y-y')$, then the system is space-invariant. For example, a technique of optical space-variant processing may be accomplished by the block diagram of Fig. 11(b). In other words, whenever a space-variant process can be decomposed as in Fig. 11(b), it may be performed by the necessary geometric transformations. The geometric transform signal can be processed by a space-invariant processor and then the required inversed geometrical transformation performed.

In a more recent article, Casasent and Psaltis[67] have shown that geometric transformations can also be accomplished by means of a nonlinear beam scanning device which writes the data onto an optical light valve. Although this method sacrifices the parallel processing capability, it can process in near real-time. Although interest in space-variant processing of photographic images is fairly recent, in view of this interest, further progress can be expected in future research.

7. ARCHIVAL STORAGE AND COLOR ENHANCEMENT

Archival storage of color films has long been an unresolved problem for film industries. The major reason is that the organic dyes used in the color films are usually unstable under prolonged storage, and this causes a gradual color fading. Although there are several available techniques for preserving the color images, all of them possess certain definite drawbacks. With one of the most commonly used techniques, that of repetitive application of primary color filters, one can preserve the color images in three separate rolls of black and white film. To reproduce the color image, a system with three primary color projectors must be used. These films should be projected in perfect unison so that the primary color images will be precisely recorded on a fresh roll of color film. However, this technique has two major disadvantages: (1) the storage volume for each film is tripled and (2) the reproduction system is rather elaborate and expensive.

In this section, we will describe a white-light processing technique for archival storage of color films. This technique may be the most efficient technique existing to date. This technique also allows direct viewing capability, and may be suitable for library applications.

The use of monochrome transparencies to retrieve color images was first reported by Ives in 1906. He introduced a slide viewer that produced color images by a diffraction phenomenon. Gratings of either different spatial frequencies or azimuthal orientation were used. More recently, Mueller[69] described a similar technique employing a tricolor grid screen for image encoding. In decoding, he used three quasi-monochromatic sources for color image retrieval. Since then, similar work on color image retrieval has been reported by Macovski,[70] Grousson and Kinany,[71] and Yu.[72]

We describe the technique[69-72] for spatially encoding the color information from a single color image onto a single black and white (BW) frame. This is done by putting a color filter, a Ronchi grating, the color frame, and the unexposed BW film together, and exposing. A triple exposure is made onto the BW film, changing the color filter (red, green, and blue) and the angular position of the Ronchi grating each time.

For example, the first exposure is made through a red filter with the grating at 0°. The second exposure is made through a blue filter with the grating oriented by 60°, and the last exposure takes place through a green filter with the grating at 120°. If the three recordings are properly recorded on the photographic film, then we have a multiplexed, spatially encoded, black and white transparency.

If we place the spatially encoded transparency at the input plane P_1 of a white-light processor shown in Fig. 1, but without the diffraction grating $T(x)$, *the different orders of the image spectra are* linearly dispersed in rainbow colors with respect to the α, α', and α'', axes. If the spatial frequency of the grating p_0 is assumed sufficiently high, then the orders of the smeared color image are physically separated.

To retrieve the color image, we allow three, first-order, smeared spectra to pass respectively through a red, a blue, and a green color filter, as shown in Fig. 12. Then three mutually incoherent primary color images will be superimposed at output plane. Thus, we see that a multicolor image is reproduced by the white-light processing technique.

Figure 13(a) shows a retrieved color image obtained with this technique. In this experiment, we used only red and green color

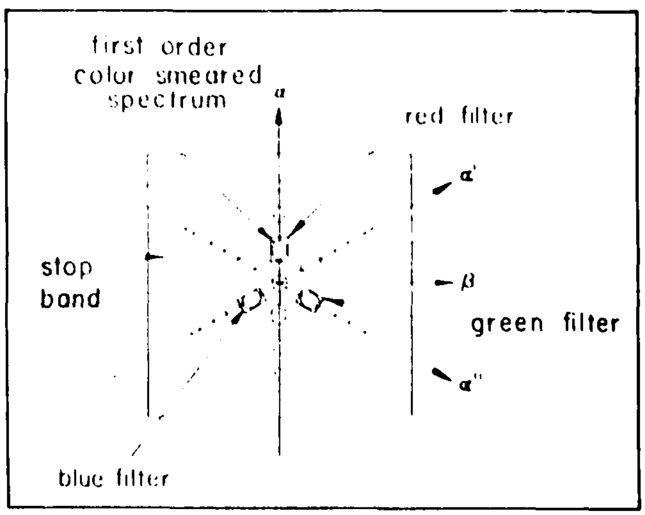

Fig. 12. Color image retrieval spatial filter (Yu, 1980[72]).

Fig. 13. *Color image recorded by multiplex technique on BW film.* (a) Original image and (b) retrieved image (Yu, 1980[74]).

Fig. 14. *Pseudocolor encoded x-ray image* (Chao, Zhuang, Yu, 1980[60]).

filters for the spatial encodings. For comparison, we provide the original color picture as shown in *Fig. 13(b)*. We see that the color reproduction by this archival storage technique is impressively faithful and the resolution is good.

An extension of the above white-light technique can be used to restore or enhance the colors in faded color films. Using a standard *coherent optical processor*, *Horner* demonstrated a similar solution for the Apollo color films degraded by radiation in outer space.

8. PSEUDOCOLOR ENCODING OF PHOTOGRAPHIC IMAGES

Most of the optical images obtained in various scientific applications are density-modulated black and white images. Human observers, however, can perceive variations in colors better than *gray levels*. Thus a color encoded image can often provide better visual discrimination. *Pseudocolor encoding by computer technique has been widely* used in applications where the images are initially digitized. While the computer technique is the logical choice for digital images, *optical processing techniques may be more advantageous for appli*cations where the initial images are analog photographic images such as aerial or x-ray photographs.

Historically the use of pseudocolor encoded filters in an imaging system was first introduced by Rheinberg in 1896. He reported the *application of color filtering in microscopy*. He showed that by simple color spatial filtering he was able to enhance small details. Burch applied color spatial filters for enhancement of orientation-dependent and high spatial frequency details. In a more recent article, Bescos and Strand proposed a color encoding technique using an extended polychromatic light source. The proposed technique encodes the image by spatial frequency rather than by density. Yu et al. have introduced an alternative approach using the one-step rainbow holographic encoding technique, where the encoding was also done in spatial frequency. The encoded holographic image can be reproduced by simple white-light illumination. Indebetouw introduced a white-light processing technique encoding the image density, in which the pseudocolor images were obtained through color filtering at the spatial frequency plane. Liu and Goodman described a technique using a specially fabricated halftone screen to obtain density pseudocolor images with coherent optical processing. Lai, Yu, and Chen adopted their halftone technique to generate pseudocolor density images with a white-light source. However, with the halftone screen, a number of discrete lines due to image sampling are generally present in the color-coded image. Thus, small details and *low contrast features of the image* can be lost in the halftone technique. A new density-pseudocoloring technique through contrast *reversal was reported recently* by Santamaria, Gea, and Bescos. Although this technique offers several advantages over previous techniques, the optical system is quite elaborate, and it requires both *incoherent and coherent sources* for the pseudocoloring. Because a coherent source is used, the coherent artifact noise may not be avoided. Recently, Yu described a simple white-light processing technique by which pseudocolor density encoding through contrast reversal can be easily obtained.[80] He showed that the white-light processing technique offers no apparent resolution loss, and the system is very simple, versatile, and economical to operate. The white-light processing system also provides a direct-viewing capability

that is essential for practical applications. However, the technique still suffers one major drawback — it is not a real-time pseudocolor-encoding technique. In a more recent article Yu described a technique of real-time white-light pseudocolor encoding in density and in spatial frequency.[81]

We will now describe a technique of contrast reversal encoding for gray level photographic images. We assume that negative and positive image transparencies of the same object are available, and we let the encodings take place on a fresh photographic film by sequential recording of the negative and the positive image transparencies with a Ronchi grating in two angular positions. For example, the first recording is exposed with the negative transparency at 0°, and the second recording is made with the positive transparency at a 90°.

If we place the spatially encoded transparency at the input plane P_1 of a white-light processor in Fig. 1, but without the diffraction grating, the smeared Fourier spectra are dispersed into the typical rainbow colors in the Fourier plane, P_2.

In pseudocolor encoding, we filter *two* first-order smeared spectra through green and red color filters, respectively, and the image irradiance at the output plane P_3 will be

$$I(x,y) = I_{ng}^2(x,y) + I_{pr}^2(x,y) , \tag{31}$$

where I_{ng} and I_{pr} are the *green color negative* and *red color positive* image irradiances. The output image is the superposition of a green negative image with a red positive image. Thus a broad range of pseudocolor density images can be obtained by the white-light processing technique. The selection of color filters is arbitrary, that is, for different color filters one would obtain different shades of pseudocolor-coded images.

In experimental demonstration we show a pseudocolor-encoded x-ray picture, as in Fig. 14. We see that a broad range of pseudocolors can be obtained by this technique, and the color coded image appears free from coherent artifact noise. We would also note that, in pseudocoloring, multicolor filters can be implemented in the Fourier spectral bands. For example, to obtain a different shade of pseudocolor, one may insert a blue filter (in blue region) with a green filter (in green region) in the same order spectral band. Thus a broad range of color combinations can be obtained by this pseudocoloring technique.

9. CONCLUDING REMARKS

We have reviewed the basic principles of coherent and incoherent optical processing techniques. We have shown that both the coherent and incoherent optical processing operations are able to be analyzed with linear system theory. Although coherent optical processing techniques have been used historically for most of the optical information processing operations, the coherent processing system is plagued with artifact noise which frequently limits its processing capability. In this paper, we have shown that there are several processing techniques which can be operated with incoherent or white-light source. Since white-light contains all the visible wavelengths, it is particularly suitable for color photographic image processing. In addition, the white-light source is generally less expensive and the system stability is not as critical as with a coherent processor.

We have described briefly the basic concepts of image deblurring, image subtraction, nonlinear processing, space-variant processing, color image retrieval and enhancement, and pseudocolor encoding of photographic images with coherent or white light illumination. We stress that the optical processing operation, either coherent or incoherent, is primarily based on the Fourier transform properties of lenses. We note that optical processing generally operates in a fixed parameter mode, and lacks the flexibility of a digital computer. Nevertheless, there still are processing operations, a few of which we have illustrated, which can be achieved with analog optical techniques, particularly with photographic images. Since spatial resolution is very important in photographic imagery, the new trends in white-light processing can be expected to open new domains in color photographic processing.

In spite of the flexibility of digital image processing, optical methods offer the advantages of greater capacity, simplicity, and lower cost. Instead of confronting each other, we can expect a gradual merging of the optical and digital techniques. The continued development of optical-digital interfaces and input devices will lead to a fruitful result of hybrid optical-digital processing techniques, utilizing the strengths of both processing operations.

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SECTION IV

Image Subtraction with Incoherent Source

Source encoding for image subtraction

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A technique of source encoding of an extended incoherent source for image subtraction is presented. The source encoding constraints are obtained from the coherence requirement for the subtraction operation. Source encoding increases the available light power for the processing operation, as a small incoherent source is no longer required. An experimental result obtained with the encoded incoherent source technique is given. A similar result obtained by using a coherent technique is included for comparison.

Optical image subtraction with complex amplitude was described by Gabor *et al.*[1] more than a decade ago. The technique involves successive recordings of two or more complex diffraction patterns on a holographic plate and the subsequent reproduction of the composite hologram images. A few years later, Bromley *et al.*[2] described a holographic Fourier subtraction technique with which a real-time image and a previously recorded hologram image can be subtracted. Although Bromley *et al.* achieved good image subtraction in their experiments it appears that the illumination for the hologram image reconstruction must be arranged carefully. In a more recent paper, Lee *et al.*[3] proposed a method whereby image subtraction and addition can also be achieved by a diffraction-grating technique. This technique involves the insertion of a diffraction grating in the spatial-frequency domain of the coherent optical processor.

However, most of the image subtraction techniques[4] require a coherent source. Such sources introduce coherent artifact noise which limits their processing capabilities. In previous papers[5,6] we have proposed a technique of image subtraction that requires an incoherent point source. However, a small incoherent source is difficult to obtain in practice. Nevertheless, this difficulty can be removed with the source-encoding technique that is discussed in this Letter.

Optical image subtraction with the diffraction-grating technique developed by Lee *et al.*[3] is basically a one-dimensional processing operation. Instead of using a point source of light, one can use a line source perpendicular to the separation of the two input object transparencies. Since the image subtraction operates upon the corresponding image points to be subtracted, a strictly broad spatial-coherence requirement is not needed. Thus it is possible to encode an extended source in order to obtain a reduced point-pair spatial coherence for the image subtraction operation.

In evaluating the spatial-coherence requirement for subtraction, we apply partially coherent imaging theory[7] at the spatial frequency plane P_3 of an optical processor, as shown in Fig. 1. The mutual coherence function is

$$\mu_3(x_3, x'_3) = \iint \mu_2(x_2, x'_2) f(x_2) f^*(x'_2) K_2(x_2, x_3) K^*_2(x'_2, x_3) dx_2 dx'_2, \quad (1)$$

where the integration is over the input plane P_2, x_2 and x_3 are the spatial-coordinate systems of P_2 and P_3, $\mu_2(x_2, x'_2)$ is the complex coherence function at the input plane P_2, $f(x_2)$ is the input object function at P_2 and can be expressed as $f(x_2) = O_1(x_2 - h_0) + O_2(x_2 + h_0)$; $O_1(x_2)$ and $O_1(x_2)$ are the two input object transparencies, and

$$K_2(x_2, x_3) = \exp\left(i2\pi \frac{x_2 x_3}{\lambda f}\right) \quad (2)$$

is the transmittance function between planes P_2 and P_3, λ is the wavelength of the light source, and f is the focal length of the transform lens L_2.

Thus the mutual coherence function immediately after the diffraction grating G, with a spatial period $d = (\lambda f)/h_0$, can be shown to be

$$\mu_3(x_3, x'_3) = \left[\exp\left(i2\pi \frac{h_0}{\lambda f} x_3\right) - \exp\left(-i2\pi \frac{h_0}{\lambda f} x_3\right)\right] \left[\exp\left(-i2\pi \frac{h_0}{\lambda f} x'_3\right) - \exp\left(i2\pi \frac{h_0}{\lambda f} x'_3\right)\right] \mu_3(x_3, x'_3), \quad (3)$$

where we ignored the dc term of the diffraction grating and $G = 1/2\{1 + \cos[2\pi(h_0/\lambda f)x_3]\}$ is a cosine grating. We note that for complex image addition of sine grating should be used. The image intensity at the output plane P_4 is

$$I(x_4) = \iint \mu_3(x_3, x'_3) \exp\left(i2\pi \frac{x_3 - x'_3}{\lambda f} x_4\right) dx_3 dx'_3, \quad (4)$$

where the integration is over the spatial frequency plane and x_4 is the output spatial coordinate system.

Let us substitute Eqs. (2) and (3) into Eq. (4) and integrate over the spatial-frequency plane. Considering only the image terms around the origin of the output plane P_4, we have

$$I_0(x_4) = |\mu_2(2h_0)||O_1(x_4) - O_2(x_4)|^2 + (1 - |\mu_2(2h_0)|)[|O_1(x_4)|^2 + |O_2(x_4)|^2]. \quad (5)$$

From Eq. (5) we see that the first term is proportional to the intensity of the subtracted image and the second term is proportional to the sum of the image irradiances,

where $|\mu(2h_0)|$ is the degree of spatial coherence. If the degree of coherence $|\mu(2h_0)|$ is high, i.e., if $\mu(2h_0) \simeq 1$, then Eq. (5) reduces to

$$I_0(-x_4) \simeq |O_1(x_4) - O_2(x_4)|^2, \quad |\mu_2(2h_0)| \simeq 1. \quad (6)$$

Thus we see that spatial coherence is required for every pair of subtracted image points. In other words, only a point-pair spatial-coherence requirement $|\mu_2(x_2 - x'_2)| \simeq 1$ for $|x_2 - x'_2| = 2h_0$ is needed for the subtraction operation.

In source-encoding, we let the intensity transmittance of the encoding mask be

$$S(x_1) = \sum_{n=1}^{N} \mathrm{rect}\left(\frac{x_1 - nd}{s}\right), \quad (7)$$

a multiple-slit source, where N is the number of encoded slits, s is the slit width, and d is the spacing between slits of the encoding mask. We note that d is also the spatial period of the grating G. At the input plane P_2, the spatial coherence function can be shown,[7]

$$\mu_2(x_2 - x'_2) = \frac{\sin\left(N\pi \dfrac{x_2 - x'_2}{h_0}\right)}{N \sin\left(\pi \dfrac{x_2 - x'_2}{h_0}\right)} \times \mathrm{sinc}\left[\pi \frac{s}{dh_0}(x_2 - x'_2)\right], \quad (8)$$

where $d = \lambda f/h_0$. From this equation we see that the last sinc factor is identical with the single-slit case, which represents a broad spread of coherence over $(x_2 - x'_2)$. However, the first factor, for large values of N, converges to a sequence of narrow pulses. The locations of the pulses (i.e., the peaks) occur at every $x = x_2 - x'_2 = n\, \lambda f/d$, which yields a spatial-coherence discrimination of $n(\lambda f/d)$ over the input plane P_2. Thus the multislit source encoding not only provides the point-pair coherence needed for image subtraction but also provides a higher available light power for the operation. In other words, the multislit encoding utilizes the light source more effectively so that the inherent difficulty of acquiring a small incoherent source can be removed.

In our experiment a mercury-arc lamp with a green filter was used as an extended incoherent source. A multislit mask was used to encode the light source. The

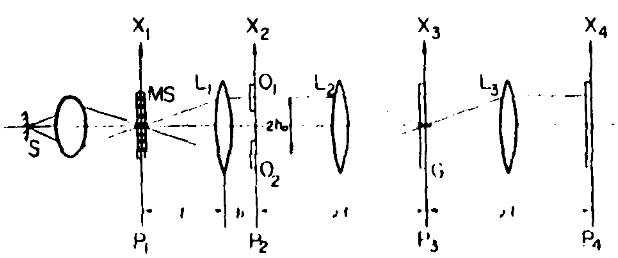

Fig. 1. Image subtraction with encoded extended incoherent source. S, mercury-arc lamp; MS, multislit mask; O_1 and O_2, object transparencies; G, diffraction grating; L, transform lens.

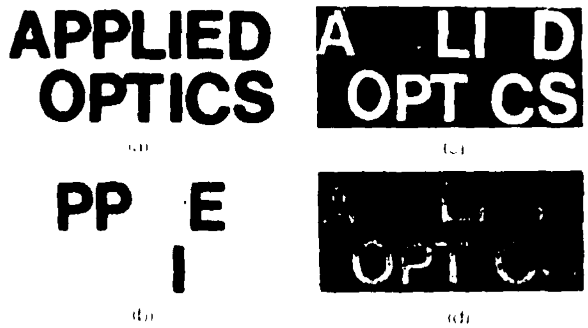

Fig. 2. Image subtraction. (a), (b) Input object transparencies, (c) subtracted image obtained with incoherent technique, (d) subtracted image obtained with coherent technique.

slit width s was 2.5 μm, the spacing between slits was 25 μm, and the overall size of the mask, which contained about 100 slits, was about 2.5 mm × 2.5 mm. The focal lengths of the transform lenses were 300 mm. A liquid gate, which contained the two object transparencies of size 6 mm × 8 mm was inserted immediately behind the collimator. A sinusoidal phase grating with a period of 25 μm was used in the spatial-frequency plane P_3. The separation between the two input images to P_2 was 13.2 mm.

In our experiments, a set of binary images as shown in Figs. 2(a) and 2(b) was used as input objects. Figure 2(c) shows the subtracted image obtained with this source-encoding technique. For comparison the subtracted image obtained with the conventional coherent processing technique is shown in Fig. 2(d). As can be seen, we obtained better artifact-noise suppression by using the incoherent technique, which results in a better subtracted image.

We have introduced a source-encoding technique for image subtraction. We stress that the concept of source encoding may be extended to other information processing operations. We also note that image subtraction with the encoded extended incoherent-source technique is generally simple, versatile, and economical to operate. It may offer a wide range of practical applications. In addition, the technique is also capable of operating in a real-time mode.

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Image subtraction with an encoded extended incoherent source

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A technique of encoding an extended incoherent source for image subtraction is presented. The source encoding is obtained from the coherence requirement for image subtraction operation. Since the coherence requirement is a point-pair concept for image subtraction the encoding can take place by spatial sampling an extended incoherent source with narrow slit apertures. The basic advantage of the source encoding is to increase the available light power for the processing operation, so that the inherent difficulty of obtaining a very small incoherent source can be alleviated. Experimental results obtained with this encoded incoherent source are given. Comparisons with the results obtained by processing technique are also provided.

I. Introduction

One most interesting and important application of optical information processing must be image subtraction. The applications may be of value in urban development, earth resource studies, meteorology, highway planning, land use, inspection, automatic tracking and surveillance, etc. Optical image subtraction may also apply to electrical and video communications as a means of bandwidth compression. For example, it is only necessary to transmit the differences between the code words or images in successive cycles rather than the whole code word or the entire image in each cycle (e.g., TV).

In 1965, optical image synthesis by complex amplitude subtraction was first described by Gabor *et al.*[1] The technique involves successive recordings of two or more complex diffraction patterns on a holographic plate and the subsequent reproduction of the composite hologram images. A few years later, Bromley *et al.*[2] described a holographic Fourier subtraction technique, for which a real-time image and a previously recorded hologram image can be subtracted. Although good image subtraction by their experiments had been reported, it appears that the illumination for the hologram image reconstruction must be arranged carefully. In 1970, Lee *et al.*[3] proposed a technique so that image subtraction and addition can also be achieved by a diffraction grating technique. This technique involves insertion of a diffraction grating in the spatial frequency domain of the coherent optical processor. Good results by the diffraction grating technique were also reported in their article. In a more recent article, Zhao *et al.*[4] also proposed a technique of image subtraction utilizing a halftone screen method. However, their technique cannot be implemented in real time.

There are several other techniques available for image subtraction which can be found in a review paper by Ebersole.[5] However, most of the optical information processing techniques require a coherent source to carry out the subtraction operation. But coherent optical processing systems are plagued with coherent artifact noise, which frequently limits their processing capabilities.

We have in previous papers[6,7] proposed a technique of optical processing with an incoherent source for complex signal detection and image deblurring.[8,9] We have also extended the technique for possible application to image subtraction.[10,11] However, to obtain a spatial coherence requirement for subtraction operation a very small source size is needed, but a small incoherent source is difficult to obtain in practice. Nevertheless, this difficulty may be alleviated with a source encoding (i.e., spatial sampling) technique, so that the extended incoherent source can be used. We have briefly discussed in a recent communication that image subtraction can indeed obtain with an encoded extended source.[12] The basic objective of source encoding is to utilize the light power more effectively so that image subtraction can be carried out with an extended incoherent source. Moreover, with the use of an incoherent source, coherent artifact noise can be avoided. We stress that this image subtraction system is capable of operating in the real-time mode, and it is generally simple, versatile, and economical.

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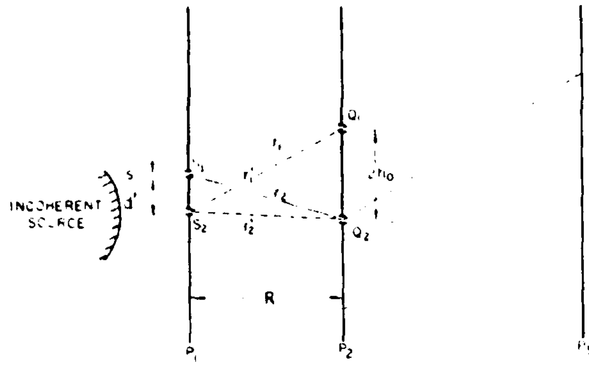


Fig. 1. Young's experiments with an extended source.

Basically, the optical image subtraction is a 1-D processing operation. Instead of utilizing a point source of light, a line source of light can be used for the subtraction operation. Since the spatial coherence requirement for subtraction operation is a point-pair concept, a strictly coherence requirement is not needed. In other words, it is possible to encode an extended incoherent source to obtain a point-pair coherence requirement for image subtraction operation.

II. Young's Experiment with Extended Source

We will now illustrate the concept of Young's experiment for the source encoding. Let us consider first a narrow slit of light source S_1 situated in plane P_1 to Fig. 1. To maintain a high degree of spatial coherence between apertures Q_1 and Q_2, the source S_1 should be very narrow. In other words, if the separation between the two open apertures is larger, the narrower incoherent source S_1 is required. It can be shown that, to maintain a high degree of coherence, the slit size can be approximated by[13,14]

$$S \approx [\lambda/(2h_0)]\, R, \tag{1}$$

where R is the distance between planes P_1 and P_2.

We now consider two narrow slits of light sources S_1 and S_2, as shown in Fig. 1. If the separation d' between the two sources S_1 and S_2 satisfies the relation

$$r_1' - r_2' = (r_1 - r_2) + m\lambda, \tag{2}$$

where the r's are the distances from sources S_1 and S_2 to the open apertures Q_1 and Q_2 as shown in the figure, m is an arbitrary integer, and λ is the wavelength of the light source, the interference fringes due to each slit source are in-phased, and a brighter fringe pattern can be observed at plane P_3. With the application of Eq. (2), we can employ many narrow slit sources since we wish to obtain a coherent fringe pattern at the output plane P_3. We note that the separations between any of the two slit sources should satisfy the fringe (i.e., spatial coherence) condition of Eq. (2). If the separation R between planes P_1 and P_2 is large, i.e., $R \gg d$, and $R \gg 2h_0$, the coherent condition of Eq. (2) becomes

$$d' = m\,[\lambda R/(2h_0)]. \tag{3}$$

From this equation we see that equal spacing slits can be used so that a brighter fringe pattern can be observed. We note that the intensity of the fringe pattern increases linearly as the number of slits increases. Thus on one hand the source encoding preserves the coherence requirement, and on the other hand it increases the overall intensity of illumination. Therefore, with appropriate source encoding, an extended source may be efficiently utilized.

III. Spatial Coherence Requirement

We will now adopt the concept of source encoding in evaluating the spatial coherence requirement for image subtraction operation. With reference to the incoherent optical processor of Fig. 2, we see that the processor is similar to that of a coherent optical processor except with an extended incoherent source and an encoding mask. Since image subtraction is a 1-D operation, we will adopt a 1-D notation for our analysis.

In evaluating the spatial coherence requirement, we use partially coherent imaging theory.[13,14] The mutual coherence function at the spatial frequency plane P_3 is

$$\mu_3(x_3,x_3') = \iint \mu_2(x_2,x_2')f(x_2)f^*(x_2')K_2(x_2,x_3) \times K_2^*(x_2',x_3')dx_2dx_2', \tag{4}$$

where the integration is over the input plane P_2; x_2, x_2', x_3, and x_3' are the position coordinates of P_2 and P_3, respectively, $\mu_2(x_2,x_2')$ is the complex coherence function at the input plane P_2; $f(x_2)$ is the input function at P_2, which can be expressed as

$$f(x_2) = O_1(x_2 - h_0) + O_2(x_2 + h_0), \tag{5}$$

where $O_1(x_2)$ and $O_1(x_2)$ are the two input object transparencies and

$$K_2(x_2,x_3) = \exp\left(i2\pi\,\frac{x_2x_3}{\lambda f}\right) \tag{6}$$

is the transmittance function between planes P_2 and P_3, λ is the wavelength of the light source, and f is the focal

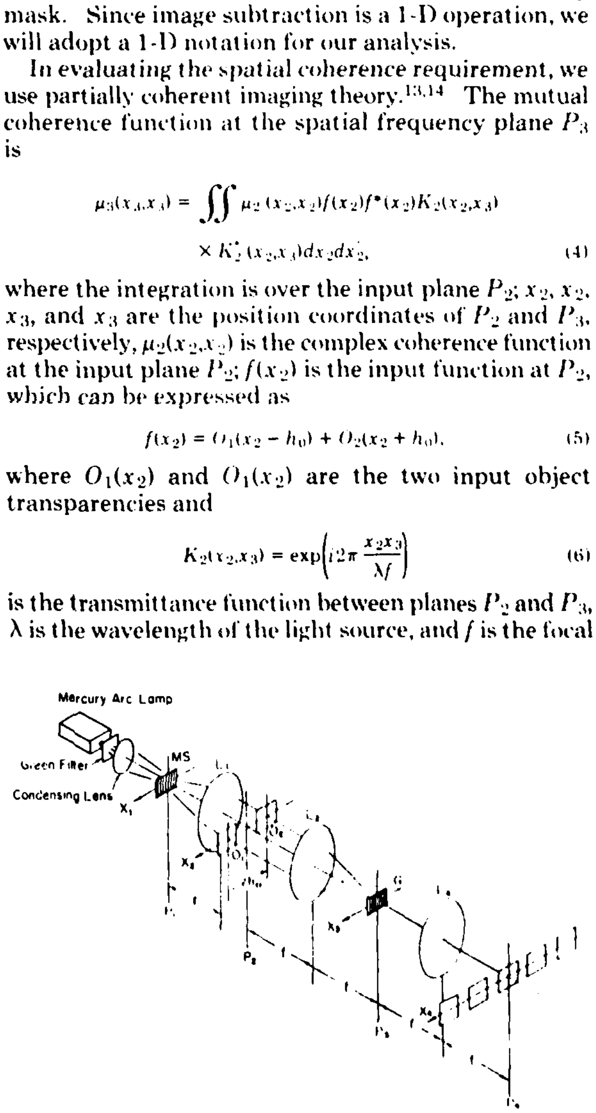


Fig. 2. Image subtraction with an encoded extended incoherent source: S, mercury arc lamp, MS, multislit mask; O_1 and O_2 object transparencies; G, diffraction grating; L, transform lens.

length of the transform lens L_2. Equation (4) can also be written

$$\mu_3(x_3,x_3') = \iint \mu_2(x_2,x_2')[O_1(x_2 - h_0) + O_2(x_2 + h_0)] \times [O_1^*(x_2' - h_0) + O_2^*(x_2' + h_0)] \times \exp\left(i2\pi \frac{x_3x_2 - x_3'x_2'}{\lambda f}\right)dx_2dx_2', \quad (7)$$

where superscript * denotes the complex conjugate.

It is clear that the mutual coherence function immediately behind the diffraction granting G, with a spacing period $d = (\lambda f)/h_0$, is

$$\mu_3(x_3,x_3') = \left[\exp\left(i2\pi \frac{h_0}{\lambda f} x_3\right) - \exp\left(-i2\pi \frac{h_0}{\lambda f} x_3\right)\right] \times \left[\exp\left(-i2\pi \frac{h_0}{\lambda f} x_3'\right) - \exp\left(i2\pi \frac{h_0}{\lambda f} x_3'\right)\right]\mu_3(x_3,x_3'), \quad (8)$$

where we ignore the dc term of the diffraction grating. The image intensity at the output plane P_4 is

$$I(x_4) = \iint \mu_3(x_3,x_3') \exp\left(i2\pi \frac{x_3 - x_3'}{\lambda f} x_4\right)dx_3dx_3', \quad (9)$$

where the integration is over the spatial frequency plane, and x_4 is the output spatial coordinate system.

By substituting Eqs. (7) and (8) into Eq. (9) and integrating over the spatial frequency plane, we have

$$I(x_4) = \iint \mu(x_2,x_2')[O_1(x_2 - h_0) + O_2(x_2 + h_0)][O_1^*(x_2' - h_0) + O_2^*(x_2' + h_0)] \cdot [\delta(x_2 + x_4 + h_0)\delta(x_2' + x_4 + h_0) + \delta(x_2 + x_4 - h_0)\delta(x_2' + x_4 - h_0) - \delta(x_2 + x_4 + h_0)\delta(x_2' + x_4 - h_0) - \delta(x_2 + x_4 - h_0)\delta(x_2' + x_4 + h_0)]dx_2dx_2', \quad (10)$$

where $\delta(x)$ is the Dirac delta function. Let us assume that $\mu(x_2,x_2')$ takes the form $\mu(x_2 - x_2')$ and $\mu(x) = \mu^*(-x)$. If we evaluate Eq. (10) termwise and note that the input images are spatially limited, we have

$$I(x_4) = \mu(o)[|O_1(-x_4)|^2 + |O_2(-x_4)|^2] - \mu(2h_0)O_1(-x_4)O_2^*(-x_4) - \mu^*(2h_0)O_1^*(-x_4)O_2(-x_4) + \mu(o)[|O_1(-x_4 - 2h_0)|^2 + |O_2(-x_4 + 2h_0)|^2], \quad (11)$$

where $\mu(2h_0) = |\mu(2h_0)| \exp(i\phi)$ is a complex quantity. We stress that phase factor ϕ can be avoided by adjusting the grating position G.

We now consider only the image terms around the origin of the output plane P_4,

$$I_0(-x_4) = |\mu(2h_0)||O_1(x_4) - O_2(x_4)|^2 + [1 - |\mu(2h_0)|][|O_1(x_4)|^2 + |O_2(x_4)|^2], \quad \text{for } \phi = 0. \quad (12)$$

From Eq. (12) we see that the first term is proportional to the intensity of the subtracted image, and the second term is proportional to the sum of the image irradiances, where $|\mu(2h_0)|$ is the degree of spatial coherence. If the degree of coherence $|\mu(2h_0)|$ is high, i.e., $\mu(2h_0) \simeq 1$, Eq. (12) reduces to

$$I_0(-x_4) \sim |O_1(x_4) - O_2(x_4)|^2, \quad \text{for } |\mu(2h_0)| \simeq 1. \quad (13)$$

Thus we see that the spatial coherence is only needed for every pair of points $|x_2 - x_2'| = 2h_0$. In other words, only a point pair spatial coherence is required for subtraction operation.

IV. Source Encoding

We will now search a source encoding so that point-pair spatial coherence can be established. We will adopt the concept of Young's experiment that we described in a previous section. Now we insert a mask transparency for the source encoding at the front focal plane P_1 of the collimator L_1 as shown in Fig. 2. The spatial coherent function $\mu(x_2,x_2')$ over the input plane P_2 can be written[13]

$$\mu(x_2,x_2') = \int S(x_1)K_1(x_1,x_2)K_1(x_1,x_2')dx_1, \quad (14)$$

where $S(x_1)$ is the intensity transmittance function of the mask, and $K_1(x_1,x_2)$ is the transmittance function between planes P_1 and P_2. We assume that the mask is located within an isoplanatic patch, and $K_1(x_1,x_2)$ can be written[13]

$$K_1(x_1,x_2) = \exp i\left[2\pi \frac{x_1x_2}{\lambda f} + \epsilon\left(x_2 - x_1\frac{b}{f}\right)\right], \quad (15)$$

where $\epsilon(x)$ is the wave aberration of the collimator, and b is the distance between the collimator and the input plane P_2.

We note that if b is sufficiently small, i.e., $(b/f)x_{1\max} \ll x_2$, the transmittance function of Eq. (15) can reduce to

$$K_1(x_1,x_2) \simeq \exp\left\{i\left[2\pi \frac{x_1x_2}{\lambda f} + \epsilon(x_2)\right]\right\}. \quad (16)$$

By substituting Eq. (16) into Eq. (14), the spatial coherence function becomes

$$\mu(x_2,x_2') = \exp i[\epsilon(x_2) - \epsilon(x_2')] \times \int S(x_1) \exp\left[i2\pi \frac{x_1}{\lambda f}(x_2 - x_2')\right]dx_1. \quad (17)$$

From the above equation we see that the spatial coherence function is the Fourier transform of the mask transmittance function modulated by a phase (wave aberration) factor. However, the phase aberration will not affect the degree of mutual coherence $|\mu(x_2,x_2')|$. In the remaining analysis, we shall ignore the phase aberration and assume that $\mu(x_2,x_2')$ takes the form $\mu(x_2 - x_2')$.

Now we evaluate the degree of coherence $|\mu(2h_0)|$ for two different cases. We will first evaluate a single-slit encoding, i.e.,

$$S(x_1) = \text{rect}\,(x_1/s), \quad (18)$$

where s is the slit width. By substituting Eq. (18) into Eq. (17), we have

$$\mu(x_2 - x_2') = \text{sinc}\frac{\pi s}{\lambda f}(x_2 - x_2'), \quad (19)$$

where the phase factor was ignored. Since the spacing

Table I. Spatial Coherence Requirement for Single-Slit Mask

s/d	1/2	1/5	1/10	1/20
$\mu(2h_0)$	0	0.756	0.936	0.988

period of the grating G, $d = (f\lambda)/h_0$, if we let $x_2 - x_2' = 2h_0 = (2f\lambda)/d$, Eq. (19) can be written

$$\mu(2h_0) = \operatorname{sinc}\left(2\pi \frac{s}{d}\right). \tag{20}$$

Thus we see that the degree of spatial coherence $|\mu(2h_0)|$ depends upon the ratio of the slit width s to the spacing d.

To gain a feeling of magnitude, we provide several values of $\mu(2h_0)$ in Table I, from which we can see that a high degree of spatial coherence can be attained only through a very narrow slit. For example, if the spacing of the grating $d = 25\ \mu m$, to achieve a high degree of spatial coherence a slit width $s \leq 2.5\ \mu m$ should be used. Thus it makes the source too weak for a practical processing operation.

As noted in the previous section, the spatial coherence requirement for image subtraction is a point-pair problem. It is possible to encode the extended source with N number of narrow slits. Thus with a multislit source encoding, an N-fold light power can be used for the image subtraction operation.

We will now let the intensity transmittance of the encoding mask be

$$S(x_1) = \sum_{n=1}^{N} \operatorname{rect}\left(\frac{x - nd'}{s}\right), \tag{21}$$

where s is the slit width, and d' is the spacing between slits.

By substituting Eq. (21) into Eq. (17), the spatial coherence function becomes

$$\mu(x) = \frac{\sin\left(N\pi \dfrac{d'x}{\lambda f}\right)}{N \sin\left(\pi \dfrac{d'x}{\lambda f}\right)} \operatorname{sinc}\left(\frac{\pi s}{\lambda f} x\right), \tag{22}$$

where $x = x_2 - x_2'$. From the above equation we see that the last sinc factor is identical to the single-slit case of Eq. (19), which represents a broad spread of coherence over x. However, the first factor for large values of N converges to a sequence of narrow pulses. The locations of the pulses (i.e., the peaks) occur at every $x = x_2 - x_2' = n(\lambda f/d')$. Thus this factor yields the fine spatial coherence discrimination at every point-pair separated at distance $(\lambda f/d')$ over the input plane P_2.

If we let the spacing of d' equal the spacing d of the diffraction grating G (i.e., $d' = d$), the spatial coherence of Eq. (22) becomes

$$\mu(x) = \frac{\sin\left(N\pi \dfrac{x}{h_0}\right)}{N \sin\left(\pi \dfrac{x}{h_0}\right)} \operatorname{sinc}\left(\pi \frac{sx}{dh_0}\right), \tag{23}$$

where we substitute $d = (\lambda f)/h_0$. From Eq. (23), we see that a sequence of narrow pulses occurs at $x = x_2 - x_2' = nh_0$, where n is an integer, and their peak values are

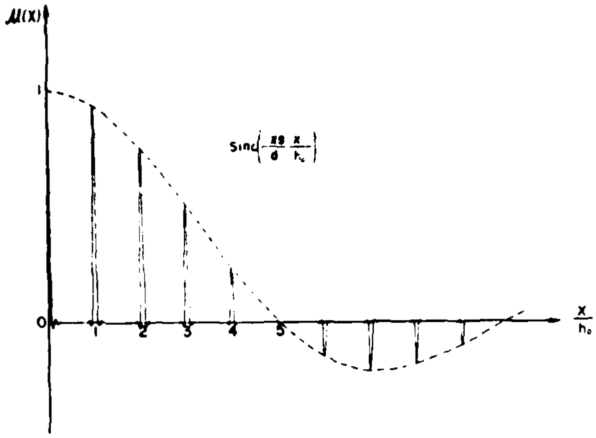


Fig. 3. Coherence function obtained with multislit source encoding, where $x = |x_2 - x_2'|$ and $s/d = 1.5$.

weighed by a broader sinc factor, as shown in Fig. 3. It can be shown that the width of the pulses is inversely proportional to the number of slits N. Thus the multislit source encoding not only provides a point-pair coherence requirement for image subtraction but also a higher available light power for the operation. In other words, the multislit encoding utilizes the light source more efficiently, so that the inherent difficulty of acquiring a small incoherent source can be alleviated.

V. Temporal Coherence Requirement

So far we have considered only the quasi-monochromatic light, but the effect of the temporal coherence has not been discussed. Since the scale of Fourier spectrum varies with wavelength, there is a temporal coherence requirement for every processing operation. With this consideration, we must limit the temporal bandwidth $\Delta\lambda$ of the source so that the dispersed Fourier spectra will not spread beyond the allowable limit. In the image subtraction operation, we should limit the spectrum spread within a very small fraction of the grating spacing d, i.e.,

$$|(p_m f \Delta\lambda)/2\pi| \ll d, \tag{24}$$

where p_m is the highest angular spatial frequency of the input objects, f is the focal length of the transform lens, and $\Delta\lambda$ is the spatial bandwidth of the source. Therefore, the temporal bandwidth of the source should be limited by the following inequality:

$$\frac{\Delta\lambda}{\lambda} \ll \frac{2\pi}{h_0 p_m}, \tag{25}$$

where λ is the center wavelength of the light source, and $2h_0$ is the separation of the input images.

To gain a practical feeling, we let $h_0 = 6.6$ mm, $\lambda = 5461$ Å and take a factor of 10 of Eq. (25). The temporal bandwidth requirements $\Delta\lambda$ for various values of spatial frequencies p_m are tabulated in Table II. We see that, if the spatial frequency of the input objects is low, a broader temporal bandwidth of the light source can be

Table II. Temporal Coherence Requirements

$\frac{p_m}{2\pi}$ (lines/mm)	0.5	1	5	20	100
$\Delta\lambda$(Å)	166	83	16.5	4.1	0.8

used. In other words, the higher the spatial frequency of the input objects, the narrower the temporal bandwidth required. We assumed that all the lenses are achromatic.

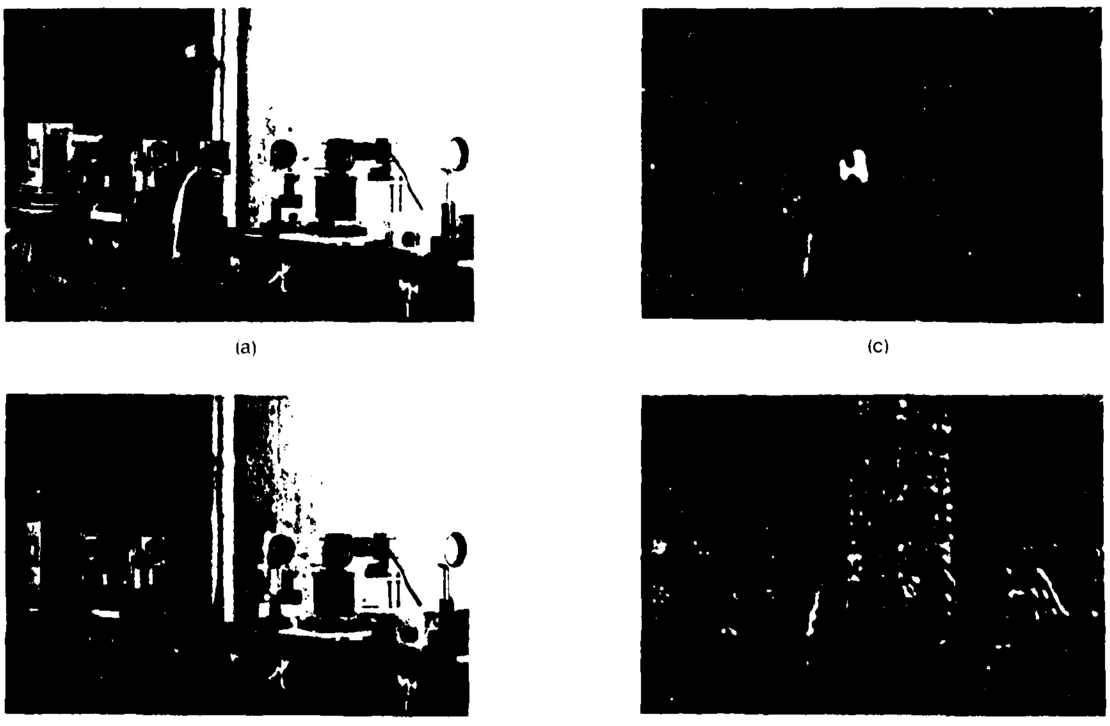
VI. Experimental Results

In our experiments, a mercury arc lamp with a green filter was used as an extended incoherent source. A multislit mask was used to encode the light source. The slit width s was 2.5 μm, the spacing of slits d' was 25 μm, and the overall size of the mask was $\sim 2.5 \times 2.5$ mm^2, which contained $\sim$100 slits. The focal length of the transform lenses was 300 mm. A liquid gate containing two object transparencies of $\sim 6 \times 8$-mm^2 size was inserted immediately behind the collimator. A sinusoidal phase grating with a spacing period of 25 μm was used in the spatial frequency plane P_3 of Fig. 2. The separation between the two input images to P_2 was 13.2 mm. We evaluated the coherence area at the input plane P_2 as $\sim 75 \times 75$ μm^2. We note that the coherence area is rather small and the spacing of the diffraction grating should be accurately matched with the spacing of the slits.

For our first demonstration, we provide two continuous tone images as input object transparencies as shown in Figs. 4(a) and (b). By comparing these two figures, we see that a liquid gate was withdrawn from the optical brench in Fig. 4(b). Figure 4(c) shows the subtracted image obtained with this incoherent processing technique, while Fig. 4(d) is obtained with the coherent processing technique. From the result obtained with the incoherent technique, a profile of a subtracted liquid gate can be seen. While from the result obtained with the coherent technique, the subtracted image is severely damaged by the coherent artifact noise. Thus we see that the incoherent technique offers a better image quality and contains virtually no coherent artifact noise.

Although a liquid gate was used in the experiment, however, the phase fluctuation created by the density fluctuation of the photographic film cannot be completely compensated. As Chavel and Lowenthal[16,17] have shown, incoherent processing can indeed suppress the phase noise effectively, which can be seen from Fig. 4(c).

For our second demonstration, we again provide two continuous tone objects of a parking lot as input object tranparencies, as shown in Figs. 5(a) and (b). From these two input object transparencies, we see that a dark gray small passenger car in a parking lot as shown in Fig. 5(a) is missing in Fig. 5(b). Figure 5(c) is the result of a subtracted image obtained from the incoherent image subtraction technique as described in this paper. In



(a) (c)

(b) (d)

Fig. 4. Image subtraction; continuous tone object: (a) and (b) input object transparencies; (c) subtracted image obtained with an incoherent technique, (d) subtracted image obtained with a coherent technique.

(a) (b) (c)

Fig. 5. Image subtraction parking lot: (a), (b) input object transparencies; (c) subtracted image obtained with an incoherent technique.

this figure, the profile of the missing passenger car can readily be seen at the output image plane P_4. It is also interesting to note that the parking line on the right side of the missing passenger car and the shadow can clearly be seen in the subtracted image of Fig. 5(c).

VII. Summary

We have introduced a source encoding technique for image subtraction. The source encoded function was evaluated from a specific coherence requirement for image subtraction operation. Since the image subtraction is a point-pair problem, and the processing is essentially a 1-D operation, it is possible to obtained a required coherence function by encoding an extended source with a set of narrow slits. In other words, the slit width, the spacing of the slits, and the number of slits determine the spatial coherence requirement.

The basic advantage of the source encoding is to increase the available light power for the processing operation, so that the inherent difficulty of acquiring a very small incoherent source can be alleviated. We stress that the concept of source encoding may be extended to other incoherent information processing operations.

Aside from the spatial coherence requirement, there is, however, a temperal coherence requirement for the image subtraction operation. If the spatial frequency requirement for the image subtraction is high, a higher temperal coherence (i.e., a narrower spectral width) of the light source is required.

In experimental demonstrations, we have shown both the results obtained with the incoherent processing and coherent processing techniques. By comparing these results, we conclude that the incoherent processing technique offers a better artifact noise suppression and better image quality.

Finally, we also stress that the incoherent image subtraction technique is generally very simple, versatile, and economical to operate. It may offer a wide range of practical applications. In addition, the technique is also capable of operating in a real-time mode.

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SECTION V

Source Encoding for Partially Coherent Processing

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Source Encoding for Partially Coherent Optical Processing

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Abstract. A relation between spatial coherence function and source encoding intensity transmittance function is presented. Since the spatial coherence is depending upon the information processing operation, a strictly broad spatial coherence function may not be required for the processing. The advantage of the source encoding is to relax the constraints of strict coherence requirement, so that the processing operation can be carried out with an extended incoherent source. Emphasis of the source encodings and experimental demonstrations are given. The constraint of temperal coherence requirement is also discussed.

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The use of coherent light enables optical processing systems to carry out many sophisticated information processing operations [1, 2]. However, coherent optical processing systems are contaminated with coherent artifact noise, which frequently limits their processing capabilities. Recently, attempts of using an incoherent source to carry out complex information processing operations had been pursued by several investigators [3–6]. The basic limitations of using incoherent source for partially coherent processing is the extended source size. To achieve a broad spatial coherence function at the input plane of an optical information processor, a very small source size is required. However, such a small light source is difficult to obtain in practice. We have, nevertheless, shown in recent published papers [7–10] that there are information processing operations which can be carried out with incoherent source. In other words, a strictly broad coherence requirement may not be needed for some optical information processing operations.

In this paper, we shall describe a linear transformation relationship between spatial coherence function and source encoding intensity transmittance function. Since the spatial coherence requirement is depending upon the information processing operation, a more relaxed coherence function may be used for a specific processing operation. By Fourier transforming this coherence function, a source encoding intensity transmittance function may be found.

The purpose of source encoding is to reduce the coherent requirement, so that an extended incoherent source can be used for the processing. In other words, the source encoding technique is capable of generating an appropriate coherence function for a specific information processing operation and at the same time it utilizes the available light power more effectively. We shall illustrate examples that complex information processing operation can actually be carried out by an encoded extended incoherent source. Experimental illustrations with this source encoding technique are also included.

Source Encoding with Spatial Coherence

We shall begin our discussion with the Young's experiment under extended incoherent source illumination, as shown in Fig. 1. First, we assume that a narrow slit is placed at plane P_1 behind an extended source. To maintain a high degree of spatial coherence between

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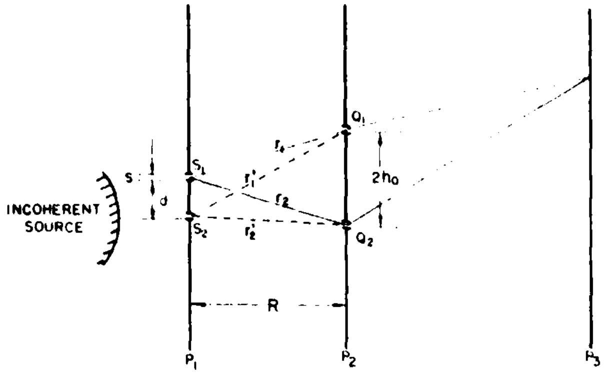

Fig. 1. Young's experiment with extended source illumination

the slits Q_1 and Q_2 at P_2, it is known that the source size should be very narrow. If the separation between Q_1 and Q_2 is large, then a narrower slit size S_1 is required. Thus, to maintain a high degree of spatial coherence between Q_1 and Q_2, the slit width should be [11]

$$w \leq \frac{\lambda R}{2h_0}, \tag{1}$$

where R is the distance between planes P_1 and P_2, and $2h_0$ is the separation between Q_1 and Q_2 (Fig. 1).

Let us now consider two narrow slits of S_1 and S_2 located in source plane P_1. We assume that the separation between S_1 and S_2 satisfied the following path length relation:

$$r_1' - r_2' = (r_1 - r_2) + m\lambda, \tag{2}$$

where the r's are the respective distances from S_1 and S_2 to Q_1 and Q_2, as shown in the figure. m is an arbitrary integer, and λ is the wavelength of the extended source. Then the interference fringes due to each of the two source slits S_1 and S_2 would be in phase. A brighter fringe pattern can be seen at plane P_3. To further increase the intensity of the fringe pattern, one would simply increase the number of source slits in appropriate locations in the source plane P_1 such that every separation between slits satisfied the coherence or fringe condition of (2). If separation R is large, i.e., $R \gg d$ and $R \gg 2h_0$, then the spacing d between the source slits becomes,

$$d = m\frac{\lambda R}{2h_0}. \tag{3}$$

From the above illustration, we see that by properly encoding an extended source, it is possible to maintain the spatial coherence between Q_1 and Q_2, and at the same time it increases the intensity of illumination. Thus, with a specific source encoding technique for a given information processing operation may result a better utilization of an extended source.

To encode an extended source, we would first search for a spatial coherence function for an information processing operation. With reference to an extended source optical processor of Fig. 2, the spatial coherence function at input plane P_2 can be written [11]

$$\Gamma(\mathbf{x}_2, \mathbf{x}_2') = \iint S(\mathbf{x}_1) K_1(\mathbf{x}_1, \mathbf{x}_2) K_1^*(\mathbf{x}_1, \mathbf{x}_2') \, d\mathbf{x}_1, \tag{4}$$

where the integration is over the source plane P_1, $S(\mathbf{x}_1)$ is the intensity transmittance function of a source encoding mask, and $K_1(\mathbf{x}_1, \mathbf{x}_2)$ is the transmittance function between source Plane P_1 the input plane P_2, which can be written

$$K_1(\mathbf{x}_1, \mathbf{x}_2) \simeq \exp\left[i\left(2\pi\frac{\mathbf{x}_1\mathbf{x}_2}{\lambda f}\right)\right]. \tag{5}$$

By substituting $K_1(\mathbf{x}_1, \mathbf{x}_2)$ into (4), we have

$$\Gamma(\mathbf{x}_2 - \mathbf{x}_2') = \iint s(\mathbf{x}_1) \exp\left[i2\pi\frac{\mathbf{x}_1}{\lambda f}(\mathbf{x}_2 - \mathbf{x}_2')\right] d\mathbf{x}_1. \tag{6}$$

From the above equation, we see that the spatial coherence function and source encoding intensity transmittance function forms a Fourier transform pair

$$s(\mathbf{x}_1) = \mathscr{F}[\Gamma(\mathbf{x}_2 - \mathbf{x}_2')], \tag{7}$$

and

$$\Gamma(\mathbf{x}_2 - \mathbf{x}_2') = \mathscr{F}^{-1}[s(\mathbf{x}_1)], \tag{8}$$

where $\mathscr{F}$ denotes the Fourier transformation operation. If a spatial coherence function for an information processing operation is provided, then the source encoding intensity transmittance function can

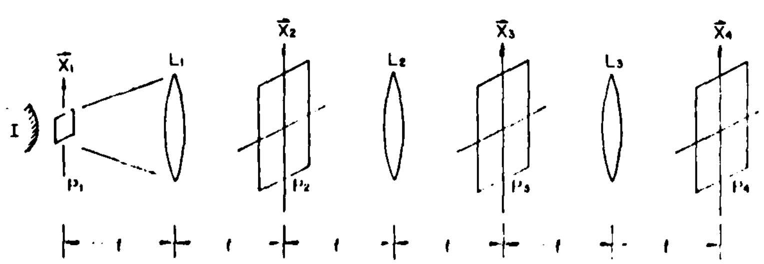

Fig. 2. Partially coherent optical processing with encoder extended incoherent source (I: extended incoherent source, L_1: collimation lens, L_2 and L_3: transform lenses)

be determined through Fourier transformation of (7). We note that the source encoding function $S(\mathbf{x}_1)$ can consist of apertures or slits of any shape. We further note that in practice $S(\mathbf{x}_1)$ should be a positive real function which satisfies the following physical realizable condition:

$$0 \leqq S(\mathbf{x}_1) \leqq 1. \tag{9}$$

For example, if a spatial coherence function for an information processing operation is

$$\Gamma(x_2 - x_2') = \mathrm{rect}\left\{\frac{|x_2 - x_2'|}{A}\right\}, \tag{10}$$

where A is an arbitrary positive constant, and

$$\mathrm{rect}\left\{\frac{x}{A}\right\} = \begin{cases} 1, & |x| \leqq A, \\ 0, & \text{otherwise}, \end{cases}$$

then the source encoding intensity transmittance would be

$$S(x_1) = \mathrm{sinc}\left(\frac{\pi A x_1}{\lambda f}\right). \tag{11}$$

Since $S(x_1)$ is a bipolar function, therefore it is not physically realizable.

Temporal Coherence Requirement

There is, however, a temporal coherence requirement for incoherent source. In optical information processing operation, the scale of the Fourier spectrum varies with wavelength of the light source. Therefore, a temporal coherence requirement should be imposed on every processing operation. If we restrict the Fourier spectra, due to wavelength spread, within a small fraction of the fringe spacing d of a complex spatial filter (e.g., deblurring filter), then we have,

$$\frac{P_m f \Delta\lambda}{2\pi} \ll d, \tag{12}$$

where $1/d$ is the highest spatial frequency of the filter, P_m is the angular spatial frequency limit of the input object transparency, f is the focal length of the transform lens, and $\Delta\lambda$ is the spectral bandwidth of the light source. The spectral width or the temporal coherence requirement of the light source is, therefore,

$$\frac{\Delta\lambda}{\lambda} \ll \frac{\pi}{h_0 P_m}, \tag{13}$$

where λ is the center wavelength of the light source, $2h_0$ is the size of the input object transparency, and $2h_0 = (\lambda f)/d$.

In order to gain some feeling of magnitude, we provide a numerical example. Let us assume that the size of the object is $2h_0 = 5$ mm, the wavelength of the light source is $\lambda = 5461$ Å, and we take a factor 10 for (13) for consideration, that is

$$\Delta\lambda = \frac{10\pi\lambda}{h_0 P_m}. \tag{14}$$

Table 1. Source spectral requirement

$\frac{P_m}{2\pi}$ [lines/mm]	0.5	1	5	20	100
$\Delta\lambda$ [Å]	218.4	109.2	21.8	5.46	1.09

Several values of spectral width requirement $\Delta\lambda$ for various spatial frequency P_m are tabulated in Table 1.

From Table 1, we see that, if the spatial frequency of the input object transparency is low, a broader spectral width of light source can be used. In other words, if higher spatial frequency is required for an information processing operation, then a narrower spectral width of light source is needed.

Examples of Source Encoding

We shall now illustrate examples of source encoding for partially coherent processing operations. We would first consider the correlation detection operation [12].

In correlation detection, the spatial coherence requirement is determined by the size of the detecting object (i.e., signal). To insure a physically realizable encoded source transmittance function, we assume a spatial coherence function over the input plane P_2 is

$$\Gamma(|\mathbf{x}_2 - \mathbf{x}_1|) = \frac{J_1\left(\frac{\pi}{h_0}|\mathbf{x}_2 - \mathbf{x}_2'|\right)}{\frac{\pi}{h_0}|\mathbf{x}_2 - \mathbf{x}_2'|}, \tag{15}$$

where J_1 is a first-order Bessell function of first kind, and h_0 is the size of the detecting signal. A sketch of the spatial coherence as a function of $|x_2 - x_2'|$ is shown in Fig. 3a. By taking the Fourier transform of (15), we obtain the following source encoding intensity transmittance function,

$$S(|\mathbf{x}_1|) = \mathrm{cir}\left\{\frac{|\mathbf{x}_1|}{w}\right\}, \tag{16}$$

where $w = (f\lambda)/h_0$ is the diameter of a circular aperture as shown in Fig. 3a,

$$\mathrm{cir}\left\{\frac{|\mathbf{x}_1|}{w}\right\} = \begin{cases} 1, & 0 \leq |\mathbf{x}_1| \leq w \\ 0, & \text{otherwise}, \end{cases}$$

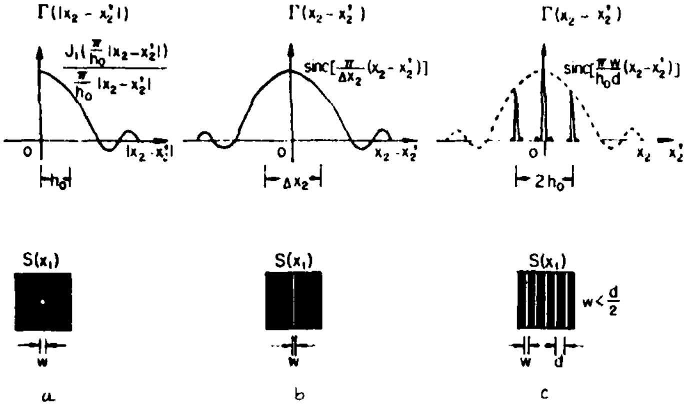

Fig. 3a–c. Examples of spatial coherence requirements and source encodings. [$\Gamma(x_2 - x_2')$: spatial coherence function, $S(x_1)$: source encoding transmittance] (a) For correlation detection, (b) for smeared image deblurring, and (c) for image subtraction

f is the focal length of the collimating lens and λ is the wavelength of the extended source. As a numerical example, we assume that the signal size is $h_0 = 5$ mm, the wavelength is $\lambda = 5461$ Å, focal length is $f = 300$ mm, then the diameter w of the source encoding aperture should be about 32.8 µm or smaller.

We now consider smeared image deblurring [13] operation as our second example. We note that the smeared image deblurring is a 1–D processing operation and the inverse filtering is a point-by-point processing concept such that the operation is taking place on the smearing length of the blurred object. Thus, the spatial coherence requirement is depending upon the smearing length of the blurred object. To obtain a physically realizable source encoding function, we let the spatial coherence function at the input plane P_2 be

$$\Gamma(|x_2 - x_2'|) = \mathrm{sinc}\left(\frac{\pi}{\Delta x_2}|x_2 - x_2'|\right), \tag{17}$$

where Δx_2 is the smearing length. A sketch of (17) is shown in Fig. 3b. By taking the Fourier Transform of (17), we obtain

$$S(x_1) = \mathrm{rect}\left\{\frac{|x_1|}{w}\right\}, \tag{18}$$

where $w = (f\lambda)/(\Delta x_2)$ is the slit width of the source encoding aperture, as shown in Fig. 3b, and

$$\mathrm{rect}\left\{\frac{|x_1|}{w}\right\} = \begin{cases} 1, & 0 \leqq |x_1| \leqq w, \\ 0, & \text{otherwise}. \end{cases}$$

For a numerical illustration if the smearing length is $\Delta x_2 = 1$ mm, the wavelength is $\lambda = 5461$ Å, and the focal length is $f = 300$ mm, then the slit width w should be about 163.8 µm or smaller.

We would now consider image subtraction [14] for our third illustration. Since the image subtraction is a 1–D processing operation and the spatial coherence requirement is depending upon the corresponding point-pair of the images, thus a strictly broad spatial coherence function is not required. In other words, if one can maintain the spatial coherence between the corresponding image points to be subtracted, then the subtraction operation can take place at the output image plane. Therefore, instead of utilizing a strictly broad coherence function over the input plane P_2, we would use a point-pair spatial coherence function. Again, to insure a physically realizable source-encoding transmittance, we would let the point-pair spatial coherence function be [10]

$$\Gamma(|x_2 - x_2'|) = \frac{\sin\left(\frac{N\pi}{h_0}|x_2 - x_2'|\right)}{N\sin\left(\frac{\pi}{h_0}|x_2 - x_2'|\right)}\,\mathrm{sinc}\left(\frac{\pi w}{h_0 d}|x_2 - x_2'|\right), \tag{19}$$

where $2h_0$ is the main separation of the two input object transparencies at plane P_2, $N \gg 1$ a positive integer, and we note that $w \ll d$. Equation (19) represents a sequence of narrow pulses which occur at $|x_2 - x_2'| = nh_0$, where n is a positive integer, and their peak values are weighted by a broader sinc factor, as shown in Fig. 3c. Thus, we see that a high degree of spatial coherence is maintained at every point-pair between the two input object transparencies. By taking the Fourier transformation of (19), we obtain the following source encoding intensity transmittance

$$S(|x_1|) = \sum_{n=1}^{N} \mathrm{rect}\left\{\frac{|x_1 - nd|}{w}\right\}, \tag{20}$$

where w is the slit width, and $d = (\lambda f)/h_0$ is the separation between the slits. It is clear that (20) represents N number of narrow slits with equal spacing d, as shown in Fig. 3c. As a numerical example, we let the separation of the input objects $h_0 = 10$ mm, the wavelength $\lambda = 5461$ Å, the focal length of the col-

limator $f = 300$ mm, then the spacing d between the slits is 16.4 µm. The slit width w should be smaller than $d/2$, or about 1.5 µm. If the size of the encoding mask is 2 mm square, then the number of slits N is about 122. Thus we see that with the source encoding it is possible to increase the intensity of the illumination N fold, and at the same time it maintains the point-pair spatial coherence requirement for image subtraction operation.

a

b

Fig. 4a and b. Photographic image deblurring with encoded extended incoherent source. (a) Input blurred object and (b) deblurred image

Experimental Results

In this section, we would illustrate two examples as obtained from the source encoding technique. The first experimental illustration is the result obtained for smeared photographic image deblurring with encoded incoherent source as shown in Fig. 4. In this experiment a Xenon arc lamp with a green interference filter was used as extended incoherent source. A single slit mask of about 100 µm was used as a source encoding mask. The smeared length of the burred image was about 1 mm.

Figure 5 shows an experimental result obtained from image subtraction operation with encoded incoherent source. In this experiment, a mercury arc lamp with a green filter was used as an extended incoherent source. A multislit mask was used to encode the light source. The slit width w is 2.5 µm and the spacing between slits was 25 µm. The overall size of the source encoding mask was about 2.5×2.5 mm^2. The mask contains about 100 slits.

From these experimental results, we see that the constraint of strictly broad spatial coherence requirement may be alleviated with source encoding techniques so that it allows the optical information processing operation can be carried out with extended incoherent source.

Conclusion

We have derived a Fourier transform relationship between the spatial coherence function and the source encoding intensity transmittance function. Since the coherence requirement is depending upon the nature of a specific information processing operation, a strictly broad coherence requirement may not be needed in practice. The basic advantage of the source encoding technique is to alleviate the constraints of the strict coherence requirement imposed upon the optical information processing system, so that the information processing can be carried out with encoded extended incoherent source. The use of incoherent source to carry out the optical processing operation has the advantage of suppressing the coherent artifact noise. In addition, the incoherent processing system is usually simple and economical to operate. Finally, we would stress that the source encoding technique may be extended to white-light optical processing operation, a program is currently under investigation.

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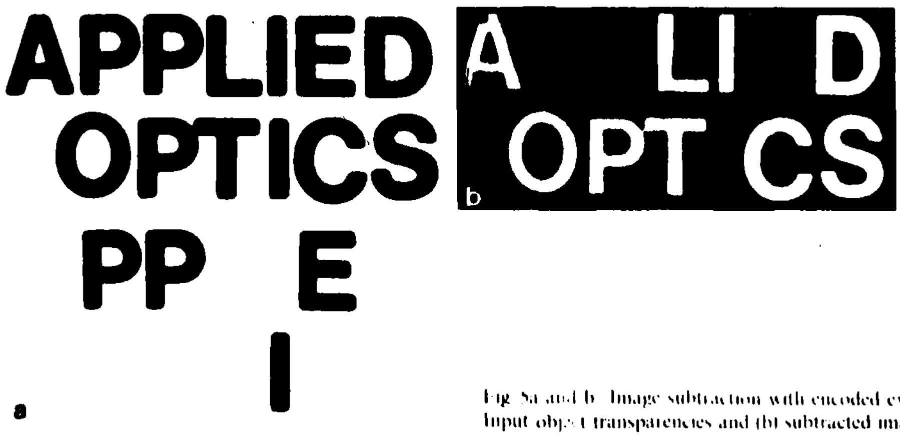

Fig. 5a and b. Image subtraction with encoded extended incoherent source. (a) Input object transparencies and (b) subtracted image

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VI. List of Publications Resulting From AFOSR Support

1. S. T. Wu and F. T. S. Yu, "Source Encoding for Image Subtraction," Optics Letters, Vol. 6, pp. 452-454, September, 1981.

2. F. T. S. Yu and J. L. Horner, "Optical Processing of Photographic Images," Optical Engineering, Vol. 20, pp. 666-676, September-October, 1981.

3. F. T. S. Yu, "Partially Coherent Optical Processing of Images," SPIE Proceedings on "Processing Images and Data from Optical Sensors," San Diego, August 24-28, 1981.

4. F. T. S. Yu and J. L. Horner, "Review of Optical Processing of Images," SPIE Proceedings on Processing Images and Data from Optical Sensors," San Diego, August 24-28, 1981.

5. F. T. S. Yu, S. L. Zhuang and T. H. Chao, "Color-Photographic-Image Deblurring by White-Light Processing Technique," Journal of Optics, (in press).

6. S. T. Wu and F. T. S. Yu, "Image Subtraction with Encoded Extended Incoherent Source," Applied Optics, Vol. 20, pp. 4082-4088, (1981).

7. F. T. S. Yu, S. L. Zhuang and S. T. Wu, "Source Encoding for Partial Coherent Optical Processing," Applied Physics, (in press).

8. S. T. Wu and F. T. S. Yu, "Visualization of Color Coded Phase Object Variation with Incoherent Optical Processing Technique," Journal of Optics, (in press).

9. S. L. Zhuang and F. T. S. Yu, "Coherence Requirement for Partially Coherent Optical Information Processing," Applied Optics, (in press).

10. F. T. S. Yu and S. T. Wu, "Color Image Subtraction with Encoded Extended Incoherent Source," Journal of Optics (in press).

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